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DESIGN AND ASSEMBLY SEQUENCE ANALYSIS OF OPTION 3 FOR CETF REFERENCE SPACE STATION

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ABSTRACT

A design and assembly sequence analysis was conducted on one option of the Dual Keel Space Station examined by a NASA Critical Evaluation Task Force to establish viability of several variations of that option. A goal of the study was to produce and analyze technical data to support Task Force decisions to either examine particular Option 3 variations in more depth or eliminate them from further consideration.

An analysis of the phasing assembly showed that use of an Expendable Launch Vehicle in conjunction with the Space Transportation System (STS) can accelerate the buildup of the Station and ease the STS launch rate constraint. The study also showed that use of an Orbital Maneuvering Vehicle on the first flight can significantly benefit Station assembly and, by performing Station subsystem functions, can alleviate the need for operational control and reboost systems during the early flights.

In addition to launch and assembly sequencing, the study assessed stability and control, orbital lifetime, and reboost propellant requirements for each sequence, and analyzed node-packaging options and the effects of keel removal on the structural dynamics of the Station. Results of these analyses are presented and discussed.

INTRODUCTION

Recently, a Critical Evaluation Task Force (CETF), composed of NASA-wide personnel, international representatives, and contractors, was formed at the NASA Langley Research Center to examine the current configuration, design, and assembly sequences for the Dual Keel Space Station (Reference 1). The efforts were in response to concerns over Space Transportation System (STS) availability, long extravehicular activity (EVA) hours estimated to assemble and maintain the Space Station, and early productive use of the Station. To address and respond to these issues, the Task Force was organized into seven major areas representing:

1. Transportation
2. EVA
3. Users
4. Configuration Integration
5. Resources
6. Safety
7. Cost

The CETF developed, analyzed, and evaluated three basic Dual Keel Space Station options. There are numerous variations within each option as is shown in Table 1. Option 1 is a constrained hardware option. It uses only hardware baselined for the Initial Operational Capability (IOC) Dual Keel Reference Configuration (Reference 1), but the assembly sequences are rephased. Option 2 focuses principally on a reevaluation of the Polar Platform. Option 3 incorporates some new or redesigned hardware elements (significantly enlarged connecting nodes to accommodate maintenance-intensive hardware).

As part of the CETF study, the Spacecraft Analysis Branch (SAB) at LaRC provided timely modeling and analysis support to the Configuration Integration Group to establish the viability of several variations in

Option 3. One goal was to produce technical data to support Task Force decisions to either examine a particular Option 3 variation in more depth or to eliminate that variation from further consideration. This paper documents the technical data that were produced during this portion of the CETF study.

SYMBOLS AND ABBREVIATIONS

A	Area
BD	Band
C & M	Controller and Monitor
C_D	Drag Coefficient
C & T	Communications and Tracking
CERV	Crew Emergency Rescue Vehicle
CETF	Critical Evaluation Task Force
CMG	Control Moment Gyro
DMS	Data Management System
E	Modulus of Elasticity
ECLSS	Environmental Control and Life Support Systems
EI	Bending Stiffness
ELV	Expendable Launch Vehicle
EPS	Electric Power System
ESA	European Space Agency
ETR	Eastern Test Range
EVA	Extravehicular Activity
FMAD	Fluid Management and Distribution
FSE	Flight Support Equipment
Gj	Torsional Stiffness
GN & C	Guidance, Navigation and Control
HAB	Habitability Module

HR & T	Heat Rejection and Transfer
I	Moment of Inertia
IOC	Initial Operational Capability
JEM	Japanese Experiment Model
LaRC	Langley Research Center
LeRC	Lewis Research Center
m	Mass
m/C_DA	Ballistic Coefficient
MDM	Multiplexer - Demultiplexer
MSC	Manned Spaceflight Center
MSFC	Marshall Space Flight Center
MSU	Mass Storage Unit
NIU	Network Interface Unit
OMV	Orbital Maneuvering Vehicle
P	Platform Flight
PIA	Payload Interface Adaptor
PMAD	Power Management and Distribution
PMC	Permanent Manned Capability
PV	Photovoltaic
RCS	Reaction Control System
RMS	Remote Manipulator System
SAB	Spacecraft Analysis Branch
SD	Solar Dynamic
SIA	Station Interface Adaptor
S/M	Structures/Mechanisms
SSRMS	Space Station Remote Manipulator System
STS	Space Transportation System

TCS	Thermal Control Systems
WTR	Western Test Range
x	Center of Mass in x-direction
y	Center of Mass in y-direction
z	Center of Mass in z-direction
ϕ_x	Rotation about x-axis
θ_y	Rotation about y-axis
ψ_z	Rotation about z-axis

DESCRIPTION OF THE STUDY

Option 3 differs from Option 1 (Table 1), in that Option 3 includes new or redesigned hardware elements (enlarged nodes) that are not used in Option 1. Twenty-eight STS flights are required in Option 3 to complete the assembly of the Space Station (17 assembly, 1 lab module outfitting, and 10 logistics flights). Four flights, which are identified as experimental platform flights in the manifest, are not included. With the limited STS availability, it is essential that the number of STS flights be reduced to shorten the station assembly time. Option 3B uses expendable launch vehicles (ELV's) and orbital manuevering vehicles (OMV's) in addition to the STS to reduce the number of STS launches to 23 and thereby significantly shortens assembly time.

The study includes evaluations of the following relative to the Task Force needs:

1) Basic changes in the Station configuration resulting from variations in Option 3 during the assembly included using larger nodes for interconnecting the modules and postponing the assembly of the keel structure assembly to a later flight than that manifested for the Dual Keel Reference Configuration (flight 12). The deferred keel assembly necessitated relocation of payloads, experiments, and a modified servicing facility from the keel to the transverse boom. Four different launch and assembly sequences for this variation have been examined and compared to the baseline sequence.

2) For the Option 3 variations, orbital assembly altitudes (including reboost strategies) have been reexamined to accommodate launches with payloads having larger masses.

3) Packaging options for the larger nodes have been examined to minimize space, to reduce crew EVA time (by launching nodes configured with equipment), and to provide a more habitable environment for the crew (by relocating noisy equipment from the HAB module to the nodes).

4) The impact of removal of the keel structure of the Dual Keel Space Station (resulting in relocating payloads from the keel to the transverse boom) on its structural dynamic characteristics using both the 5-meter bay

erectable and the 9-foot bay deployable trusses has been analyzed. Potential interactions with the on-board control system have been examined.

ASSEMBLY PHASING ANALYSIS

The five launch/assembly sequences that have been examined in the study are designated as follows:

1. Sequence 1 (baseline, CETF designation Option 3)
2. Sequence 2 (CETF designation Option 3B, Version 1)
3. Sequence 3 (CETF designation Option 3B, Version 3)
4. Sequence 4 (CETF designation Option 3B, Version X)
5. Sequence 5 (CETF designation Option 3A)

The sequences use both different assembly phasing and different modes for placing the payloads in space. The modes are combinations of STS and Titan 4 (ELV) launches. The goals are to provide an earlier man-tended and permanently manned Station, early payload and/or servicing accommodations, and a reduction in crew EVA time for assembly and maintenance. Only the first seven flights of each sequence were examined because flights beyond flight 7 are approximately the same for all sequences. However, for sequence 2, only the first three flights were examined since assembly payloads are identical to sequence 1. Figure 1 shows the flight timetable for all five sequences through flight 8 along with the orbit insertion and rendezvous altitudes of each flight. The assembly phasing (launch manifest) for all 5 sequences is given in Table 2. Launch manifests including payload description (components and masses) are given in Appendix A for sequences 2 through 5. Figures illustrating the configuration for each assembly phase of sequences 2 through 5 are given in Appendix B.

Sequence 1 (Baseline, CETF designation Option 3)

The baseline sequence utilizes only the STS for delivery of Space Station hardware to orbit. Table 2(a) gives the sequence 1 manifest which includes 28 STS flights to complete the assembly of the Space Station. The 4 experimental platform flights that are not involved in the assembly process are not listed. Modification of the baseline sequence allows direct comparisons with other sequences in this study. Assembly time for the revised baseline sequence is approximately 18 months through flight 7 (assuming 3 months between flights) and 81 months for complete assembly of the Station.

Sequence 2 (CETF designation Option 3B, Version 1)

Differences in the launch/assembly phasing for sequences 1 and 2 are less than for other sequences (Tables 2(a) and (b)). Whereas sequence 1 uses only STS flights for assembly, sequence 2 uses an ELV for the first flight. The assembly scenario consists of a flight 1 (ELV) launch date that is approximately one week prior to flight 2 (STS). A rendezvous of the payloads from flights 1 and 2 occurs at an altitude of 220 nmi. Flight 3 occurs approximately three months later. After assembly of payloads from flights 1 through 3, the remaining launch and assembly sequences are identical to sequence 1. The time required for assembly of sequence 2 through flight 7 is approximately 15 months.

Sequence 3 (CETF designation Option 3B, Version 3)

Sequence 3 (Table 2(c)) offers additional capabilities that are not offered by either sequence 1 or sequence 2. These capabilities are an early phased servicing facility, where some servicing capabilities are brought up on earlier flights, and the use of an OMV, allowing for lower rendezvous altitudes and thus higher payload-launched mass by the STS and ELV. The STS is used for launching the first three flights to the assembly orbit. Flight 1 manifests a fully loaded OMV to provide reboost of each assembly sequence to a designated altitude. ELV launches are used for the fourth and sixth flights. The early servicing facility is launched on STS flight 3. In comparison, sequence 1 (Table 2(a)) has servicing capabilities after flight 16. The sequence 3 Station is man-tended after flight 5 and permanently manned after flight 7. In contrast, the sequence 1 Station is man-tended after flight 5 and permanently manned after flight 9.

The launch scenario consists of an ELV launch approximately one week prior to the fourth STS launch. At this time, the ELV payload, STS, and partially assembled Station rendezvous at a designated altitude. The specified rendezvous altitude for this sequence is 150 nmi. STS launches proceed every three months thereafter. To arrive at the rendezvous altitude coinciding with these STS launches, the partially assembled Station is transferred by the OMV up to an altitude such that the Station orbit will decay down to the 150-nmi rendezvous point at the end of the nominal 90-day period.

A reduction in time of approximately 6 months to assemble the Station through flight 7 is achieved by using ELV flights. Therefore, a fully operational Station is assembled in a shorter time than for sequences 1 and 2.

Sequence 4 (CETF designation Option 3B, Version X)

The launch/assembly sequence for sequence 4 (Table 2(d)) is a variation of sequence 2 (Table 2(b)). Sequence 4, however, incorporates an additional ELV launch (flight 5) and the use of an OMV. The first launch (flight 1), an ELV launch, differs from sequence 2 by the addition of the "smart" section of the OMV instead of the non-operational control moment gyro (CMG) package manifested for sequence 2. This "smart" section provides attitude stabilization control when the payload is released from the Titan. An early servicing facility is launched in flight 3, and the Station is permanently manned after flight 7 (as is the case for sequence 3).

The launch scenario, again, consists of ELV launches which are scheduled one week prior to STS launches. The rendezvous altitude, however, is variable, a departure from the rendezvous operation plan proposed for the two previous sequences. Flights 1 through 4 have a rendezvous altitude of 150 nmi, flights 5 and 6 have an altitude of 170 nmi, and flight 7 is at 180 nmi. The variable altitudes allow larger payloads to be launched at the lower altitudes and provide a safety factor to account for orbital decay at the higher altitudes. To meet the rendezvous altitude requirement, the partially assembled Station is reboosted (using the OMV system brought up on flights 1 and 2) to an altitude equal to the rendezvous altitude plus 90 days (as is the case for sequence 3).

Again, the use of a mixed launch fleet (ELV and STS) reduces the time needed to assemble the Station through flight 7 by 6 months. Because two

ELV flights are used in sequences 3 and 4, the time to flight 7 for sequences 3 and 4 is identical (12 months).

Sequence 5 (CETF designation, Option 3A)

Sequence 5 (Table 2(e)) utilizes only the STS as a launch vehicle but includes the use of an OMV. The use of the OMV makes this sequence different from sequence 1 (Table 2(a)). Many other advantages present in the other sequences are also contained in this sequence, namely early phased servicing, variable rendezvous altitudes to allow for heavier payloads, and incorporation of the OMV. However, because the STS is the only launch vehicle used, the time required to reach the configuration after flight 7 (18 months) is the same as for sequence 1. Total time of assembly for the sequence 5 Station is 81 months.

The rendezvous altitudes vary to allow for heavy launch payloads in the lower rendezvous altitudes. Flights 1 and 2 are launched to an altitude of 150 nmi, and the remaining flights are launched to 190 nmi. The higher altitude is used after the second flight to provide some margin of safety for orbital decay.

STABILITY AND CONTROL ANALYSIS

For each assembly sequence examined, an assessment of the rigid-body stability and control requirements has been performed using a rigid-body control dynamics analysis program. This program incorporates articulating subsystems in the orbital calculation (Reference 2). For consistency between calculations, the geometric center of the fully assembled transverse boom has been used as the origin for each assembly sequence. The initial attitude of the Station is such that the X-axis is directed along the flight path, the Z-axis is Nadir pointing, and the Y-axis is perpendicular to the orbit plane. The attitude angles presented are the Euler angle rotations from the initial attitude to the flight orientation attitude associated with each flight.

Based on the mass and area properties of each flight configuration, the environmental forces and torques acting on the Station are determined and resolved into angular momentum requirements for attitude control. For each flight, the control assessment has been performed at the rendezvous plus 90 days altitude using the 2 sigma Jacchia atmospheric model of Reference 3. Figure 2 illustrates the density variations of this atmospheric model.

Sequence 2 (CETF designation Option 3B, Version 1)

Sequence 2 differed from sequence 1 in only the first three flights, as can be seen from the flight manifest (Table 2). Therefore, unlike the other sequences examined, comparisons between sequences 1 and 2 need only be made through flight 3. A summary of mass and inertia properties of the Station for sequence 2 is given in Table 3. The center-of-mass distances are measured from the origin of the Station (geometric center of fully assembled transverse boom). The first flight, an ELV launch, is presented to illustrate the stability characteristics of the payload. Stability of the flight 1 payload after it is placed into orbit is a major concern because this payload does not have an attitude control system to provide stability.

An examination of the inertia properties shows that the payload will be stable if it is flown in a gravity-gradient orientation. However, because release from the Titan applies a measure of tip-off rate to the payload, the initial release may produce large payload oscillations initially in spite of the inherent stability characteristics of the payload. The results obtained from the analysis of this ELV launch have been assumed to approximate all ELV launches used to assemble the Station. The concern about large payload oscillations was alleviated in sequence 4 by including an attitude stabilization and control system (provided by the "smart" section of the OMV) in flight 1.

The attitude control requirements for flights 2 and 3 are shown in Table 4. The orientation for flight 2 was trimmed with the transverse boom directed along the Nadir and with the payload from flight 1 nearest to the Earth. Flight 3 was flown in the standard trimmed flight orientation. Two sets of values for the control requirements and the attitude Euler angles for flight 3 are given in Table 4. The first set of requirements results when the maximum 5-degree attitude limit is reached (although this could be relaxed during the early assembly flights). The other set (in parentheses) results when the Station is fully trimmed to reduce the secular angular momentum buildup. The Euler angles for the latter case, however, greatly exceed the 5-degree limit. The 5-degree limit does not produce a large increase in the peak angular momentum; however, it does produce an increase in the secular angular momentum, requiring a more frequent desaturation of the control moment gyros (CMG's).

Sequence 3 (CETF designation Option 3B, Version 3)

The mass and inertia properties of the Station for assembly sequence 3 are shown in Table 5. Analyses have been performed only for flights in which the addition of payloads to the Station results in a different Station configuration. For example, flight 4 ELV launch is attached to the Station concurrent with the STS flight 5 payload. Therefore, only the configuration after flight 5, the Station configuration after the attachment of payloads from flights 4 and 5, is analyzed. One noteworthy result produced from the analysis was a significant decrease in the moment of inertia about the Z-axis between flights 2 and 3. This decrease is due to the relocation of the OMV from the end of the transverse boom near the photovoltaic module in flight 2 to the center of the transverse boom in flight 3. This relocation produced lower gravity-gradient torques for the flight 3 configuration.

The control requirements for assembly sequence 3 of the Station are shown in Table 6. Two orientations were used for flights 1 and 2. In the first orientation, an "arrow" orientation, the transverse boom is parallel to the flight path. In the second orientation, the transverse boom is directed toward the Nadir. Both orientations are illustrated by the attitude angles $\phi_{(x)}$, $\theta_{(y)}$, and $\psi_{(z)}$ (90 plus Euler angles) as shown in Table 6. The numbers in parentheses in Table 6 are the angles at which the Station is trimmed to minimize the secular momentum buildup. A trim angle restricted to values of 5 degrees or less was used for all remaining flights. The results show that the Station configuration after flights 1 and 2 is aligned in a Nadir-pointing orientation resulting in a substantial decrease in the angular momentum control requirements. The control requirements for flights 3 and 5 are dominated by the secular momentum buildup. The buildup is due to the 5-degree restriction on the trim angle, resulting in an inability to reduce the secular momentum to desirable levels. The calculation of the number of CMG's required for flights 3 and 5 is based upon the assumption that desaturation occurs approximately every orbit. The maximum number of equivalent Skylab CMG's that are required for flight 7 is four.

Sequence 4 (CETF designation Option 3B, Version X)

This sequence is similar to sequence 3 in that it also has an early servicing facility, the use of an OMV, and an ELV launch as the first launch. The possibility of tumbling of the flight 1 payload from tip-off rates imparted when the payload is released from the Titan has been alleviated by including an attitude control system (provided by the OMV) in flight 1. The other significant change from other sequences is the removal of the OMV after flight 5 for servicing. The mass and inertia properties for the flights in sequence 4 are shown in Table 7. The properties do not differ significantly from values for other sequences.

The control requirements for sequence 4 are similar to those for sequence 3. These results are shown in Table 8. Following the results for sequences 2 and 3, two sets of data are also given for this sequence, one for the 5-degree attitude limited case and one for the fully trimmed case (in parenthesis). For flight 2, the transverse boom is aligned in the direction of the Nadir (which is illustrated by the attitude angles, 90 plus Euler angles); the control requirements for this flight are very small. For flights 3 through 6, the very large trim angles produce an attitude angle which exceeds the 5-degree attitude limit. For the 5-degree limited cases, the peak angular momentum is equal to the secular angular momentum, resulting in larger torque control requirements than the fully trimmed case and more frequent desaturation of the CMG's.

Sequence 5 (CETF designation Option 3A)

Flights 4 through 6 are very similar in sequences 3 and 5. Therefore, only flights 1, 2, 3, and 7 were examined in detail to expedite the analysis. The mass and inertia properties of the Station for sequence 5 are presented in Table 9 and include information for all flights. The most noteworthy characteristic of these data is, again, the decrease in the Y moment of inertia because of the relocation of the OMV to the origin of the Station.

The control requirements for flights in sequence 5 are shown in Table 10. The first two flights have a trimmed orientation with the transverse boom pointing in the direction of the Nadir. The orientation for the remaining flights is fully trimmed about each axis to reduce secular momentum buildup. These trim angles did not, however, exceed the 5-degree limit. The equipment for flights 1 and 2 does not include CMG's; for this reason, a determination of the number of CMG's required for attitude control is not appropriate. Attitude control for these two flights is provided by the OMV. The largest control requirements occur for flight 7; however, they are approximately one-half as large as the control requirements for flight 7 of sequence 3. This reduction is due to a smaller servicing capability manifested for sequence 5.

ORBITAL LIFETIME AND REBOOST PROPELLANT ANALYSIS

The technique described in Reference 4 was used to calculate Space Station orbital lifetimes for each flight in assembly sequences 2 through 5. The specific ballistic coefficient (mass/(drag coefficient x area)) and actual launch date for each flight were used in the calculations. Atmospheric density profiles for drag calculations were obtained from the 2 sigma Jacchia model (Reference 3). The orbital lifetime data include the launch date, rendezvous altitude, the time to decay from various altitudes (220 and 180 nmi) to the rendezvous altitude, the remaining orbital lifetime in the absence of reboost, and the altitude which constitutes the rendezvous plus 90-day decay altitude. The rendezvous altitude shown in the tables for a given flight corresponds to the altitude required to rendezvous the Station with the subsequent launch.

Sequence 2 (CETF designation Option 3B, Version 1)

The orbital lifetime characteristics for the second and third flights of sequence 2 resulted in ballistic coefficients of 72 kg/m^2 and 18 kg/m^2, respectively. The rendezvous altitude for the flights is 220 nmi. Therefore, based upon a three-month separation between launch dates (which results in different atmospheric density profiles for each launch), the flights have orbital lifetimes (without any orbit-keeping operations) of 132 and 38 days, respectively. Unlike the other sequences, the Station is not boosted to higher altitudes in this sequence and then allowed to decay. Therefore, an active orbit-keeping propulsion system is mandatory for this assembly sequence.

Sequence 3 (CETF designation Option 3B, Version 3)

Table 11 gives the orbital decay information for each flight (except ELV flights 4 and 6) in sequence 3. The ballistic coefficients for flights 1 and 2 are large because the projected drag area for each flight is small. The small area is due to the flight orientation and the orientation of the solar arrays and radiators to provide minimum drag area. The remaining flights have a reduced ballistic coefficient because of the need for solar tracking of the solar arrays and anti-solar tracking of the radiator to provide the necessary power and heat rejection for the station. The need for tracking resulted in larger projected areas for the assembly sequences. In comparing the orbital lifetimes between flights, the lifetimes did not necessarily decrease with decreasing ballistic coefficient. For example, flight 1 has a shorter lifetime than flight 7, even though the ballistic coefficient of flight 1 is larger than that of flight 7. This is due to a decrease in atmospheric density at the launch date of the later flight when compared to the density for the earlier flight. Therefore, comparison of ballistic coefficients, in and of itself, is not enough for evaluation of orbital lifetime performance of the various flights. The rendezvous altitude for each flight is shown in Table 11 and is 150 nmi for all flights.

Sequence 4 (CETF designation Option 3B, Version X)

The orbital lifetime parameters for sequence 4 (except ELV flights 1 and 5) are given in Table 12. As was the case with sequence 3, flight 2 has a large ballistic coefficient because of the minimization of projected area. The need for power and heat rejection greatly reduced the ballistic coefficients of subsequent flights. The areas shown for flights 3-7 did not change because once the solar arrays and radiator were fully deployed and operational, they dominated the drag areas of each flight.

Sequence 5 (CETF designation Option 3A)

Table 13 gives the orbital lifetime parameters for sequence 5. The results for this sequence followed the trend set in sequences 3 and 4, with large ballistic coefficients through flight 2 and large projected areas for the remaining flights.

REBOOST PROPELLANT REQUIREMENTS ANALYSIS

Generic Orbital Lifetime Profiles

Orbital lifetimes of the Space Station have been established for various ballistic coefficients, initial altitudes, and two atmospheric density models and are presented in Appendix C. Ballistic coefficients of 20, 50, and 100 kg/m^2 were used to bracket the expected range for the Station assembly sequences for quick interpolations and lifetime estimates. Initial altitudes of 150, 190, 220, and 250 nmi have been used. These altitudes span the expected range of possible altitudes at which the Space Station will operate. Finally, two atmospheric models, a nominal and a 2-sigma atmosphere, were used to cover the possible atmospheric density variations. All results have been plotted for the initial launch date of January 15, 1993.

Reboost Propellant Requirements

The reboost propellant requirements for Option 3 are shown in Figure 3. The propellant requirements have been calculated using the mass of the Station configuration, the rendezvous altitude for the next payload flight (190 nmi), and the 90-day decay plus rendezvous reboost altitude required for the partially assembled Station (which is a function of the Station's ballistic coefficient and the atmospheric density variation based on the date of reboost). Figure 3 shows the propellant requirement for on-schedule launches (on 90-day cycles) as well as the propellant required for missed launches (on 180-day cycles). The reboost altitudes to provide for decay to the rendezvous altitude in 90 days are given in the lower part of the figure. These curves were generated using the 2 sigma atmospheric density profile estimated for January 15, 1993 from the generic profiles for orbital lifetime found in Appendix C. Because the density does decrease for subsequent reflights, the actual reboost altitudes and propellant mass requirements in the later assembly phase will be significantly lower than shown.

NODES PACKAGING ANALYSIS

Rationale for Moving External and Habitability (HAB) Module Equipment to Pressurized Nodes

The reason for moving the external equipment into a pressurized node is to reduce the EVA time required to install and repair the equipment. The advantages of moving the ECLSS equipment from the HAB module to the node are as follows: 1) to provide more privacy for the crew, 2) to provide more living space for the crew, 3) to remove inherently noisy equipment from the crew quarters, 4) to retain crew waste collection and processing equipment in one location, and 5) to keep objectionable odors away from the living quarters.

Nodes and Racks Configurations

Of the four nodes used in the IOC Station, 3 and 4 have been considered for packaging. These nodes are not connected to any international modules as shown in Figure 4. A nodal diameter of 3.66 m (12 ft.) has been used in the analysis. The nodes and equipment rack configurations are shown in Figures 5 and 6, respectively. The 10.2 cm (4-in.) space on the back and the 15.2 cm (6-in.) space on the side of the rack are reserved for wiring, etc. The available volume of the rack is 1.69 m^3 (59.8 cu. ft.) but after removing the volume required for wiring, the available volume of the rack is reduced to approximately 1.37 m^3 (49 cu. ft.). Equipment considered for packaging into the nodes includes portions of the external and water recovery management equipment and all the waste management equipment. Only volumes and not actual dimensions of the equipment have been used in the analysis.

Candidate External Equipment

The list of candidate external equipment for relocation into the pressurized volume is shown in Table 14. Weights, volumes, volumes including packaging, and power requirements for the following equipment are given: communications and tracking (C&T); data management system (DMS); fluid management and distribution (FMAD); guidance, navigation and control (GN&C); heat rejection and transport (HR&T); electric power system (EPS); and structure/mechanism (S/M). The volumes including packaging have been derived by dividing the volume obtained from a McDonnell Douglas study (Reference 5) by a factor of 0.6. By consensus, the CETF determined that a scaling factor of 0.6 was appropriate because the equipment density used in the McDonnell Douglas study was too high. A density on the order of 322 kg/m^3 (20 lb/cu. ft.) is more appropriate. Therefore, a factor of 0.6 was arbitrarily selected by the CETF for use in this analysis.

External Equipment Moved to Node 3

The packaging of the external equipment into node 3 is shown in Table 15. All candidate external equipment can be packaged into node 3, and only three of four racks are used. Rack 1 contains C&T and GN&C for a total volume of 1.36 m^3 (48 cu. ft.), rack 2 contains DMS and S/M for a total volume of 1.34 m^3 (47.4 cu. ft.), and rack 3 includes FMAD, HR&T, and EPS for a total volume of 1.07 m^3 (37.6 cu. ft.).

Candidate HAB Module Equipment

The list of the candidate HAB module equipment that can be moved to the nodes is shown in Table 16. The equipment weights, volumes, and power requirements are based upon a six-person crew. The volumes, which include 15% for packaging (volume of equipment + 15%), were obtained from the NASA Marshall Space Flight Center (MSFC). Later, MSFC indicated that the 15% equipment packaging volume used is not adequate. Martin Marietta (Reference 6) recommended to the CETF a packaging volume of 26.4%. Table 16 shows the quantities, weights, volumes including 15% packaging (MSFC volume), volumes including 26.4% packaging (Martin Marietta recommended volume to CETF), and power requirements for the waste management equipment and a portion of the water recovery management equipment. The waste management equipment candidates are urine collection, fecal collection and processing, trash collection and processing, and general housekeeping. The water recovery management equipment candidates are urine processing, urine processing controller, hygiene water processing, hygiene processing controller, water thermal conditioning, and common module service. The candidate HAB module equipment was selected by the CETF because the consensus of the CETF was that only non-life-critical ECLSS equipment should be considered as candidates for packaging. EPS is also required in this candidate package.

HAB Equipment Moved to Node 4

The candidate HAB module equipment used for packaging into node 4 is shown in Table 17. Although hygiene water processing, the hygiene water processing controller, water thermal conditioning, and the common module service are listed as candidates, they have not been considered for packaging into node 4. This equipment was not considered because the common module service, which is too large to fit into a rack, will remain in the HAB module. Long lines of pipe running from the HAB module to node 4 are then required to process waste water if the hygiene water processing/controller and the water thermal conditioning are moved to node 4. Rack 1 contains urine collection, urine processing, and the urine processing controller. The equipment occupies a total volume of 1.28 m^3 (45.5 cu. ft.). The contents in rack 2 are EPS and fecal collection and processing with a total volume of 1.07 m^3 (37.7 cu. ft.). Rack 3 includes trash collection and processing and general housekeeping; this equipment occupies a total volume of 0.88 m^3 (31.3 cu. ft.). Rack 4 is vacant and can be used to package portions of the water recovery management equipment if needed.

Nodes Packaging Results

The analysis based on equipment volume shows that it is possible to move all the candidate external equipment and some of the non-life-critical ECLSS HAB module equipment (urine collection, urine processing, urine processing controller, fecal collection and processing, trash collection and processing, general housekeeping, and EPS) into pressurized nodes. The total volume of the candidate external equipment that can be moved to node 3 is 3.77 m^3 (133 cu. ft.). The non-life-critical ECLSS HAB module equipment candidates that can be moved to node 4 occupy 3.23 m^3 (114.5 cu. ft.), volume that will then be free in the HAB module. If the hygiene water processing, the hygiene water processing controller, and the water thermal conditioning are considered for relocation into node 4, then an additional volume of 0.65 m^3 (23 cu. ft.) can be off-loaded from the HAB module.

ANALYSIS OF KEEL REMOVAL EFFECTS ON STATION STRUCTURAL DYNAMICS

As part of a more comprehensive analysis performed by the Spacecraft Analysis Branch, the effects of removing the keel structure from the Dual Keel Space Station on the structural dynamics of the Station and the interaction of the removal with the on-board attitude control system have been examined. The effects of using either the 5-meter bay erectable truss or the 9-foot bay deployable truss have also been examined. Figure 7 illustrates the two concepts. The first concept is the reference CETF Dual Keel configuration with several attached payloads and experiments. The second concept is the first concept without the dual keel. Payloads that were attached to the upper and lower sections of the keel in the first concept are relocated to points along the transverse boom in the second concept. Therefore, the same payloads are carried by both configurations with the exception of the tether and the large antenna. These latter items were eliminated in the second concept because of attachment constraints.

The two Station configurations have been modeled using finite-element methods (Reference 7) in which a linearized structural model is created. The mode shapes and frequencies are determined from the eigenvectors and eigenvalues of the finite-element model. An analogous beam model has also been used to represent the truss structure; lumped masses with appropriate inertia properties were included to represent the various attached payloads. The beam model has identical mass and stiffness characteristics (both bending and torsion) as those for the actual truss structure. Structural modeling of this type allows for a large reduction in computational time while still providing analytical integrity of the results. The physical and material properties used for both the 5-meter bay and the 9-foot bay trusses are shown in Figure 7.

The natural frequencies and a description of the mode shapes for both structural configurations and the two types of truss structures are also shown in Figure 7. To provide a more direct comparison between models, the modes involving primarily solar array motion are not presented. As shown in the results, the absence of the keel structure does not dramatically decrease the natural frequencies of the structure. In the case of the first two modes, which are bending modes of the transverse boom, the frequencies decrease by no more than 4 percent. The frequencies of modes involving transverse boom twisting increase significantly when the keel is removed. This is due to the elimination of the additional off-set mass and inertia that the keel and keel-attached payloads provide, thereby allowing the structure to twist more freely.

The use of the 9-foot bay truss as the main structural element of the Station results in natural frequencies that are slightly less than one half those for the 5-meter bay truss. Structural frequencies are of concern because if they are low enough, they can interact with the control system bandwidth of the Station. The estimated bandwidth of the Space Station control system is 0.01 Hz. Therefore, a separation of the fundamental frequency and the control system is present even for the case of the 9-foot bay truss. The low frequency, however, results in larger structural vibrational amplitudes.

SUMMARY

A design and assembly sequence analysis was conducted on Option 3 of the Dual Keel Space Station configuration examined by a NASA Critical Evaluation Task Force (CETF). The purpose of the study was to establish the viability of several variations of Option 3.

The assembly phasing analysis showed that use of an ELV in place of the STS can accelerate the buildup of the Station and ease the STS launch rate constraints. The study also showed that use of an OMV on the first flight can significantly benefit the Station assembly and, by performing Station subsystem functions, can alleviate the need for operational control and reboost systems during the early flights.

In addition to launch and assembly sequencing, the study assessed stability and control, orbital lifetime, and reboost propellant requirements for each sequence, and analyzed node-packaging options and the effects of keel removal on the structural dynamics of the Station. Results of these analyses include:

1. Angular momentum requirements for attitude control for each sequence.
2. Decay time from various altitudes to rendezvous altitude and remaining lifetime without reboost.
3. Reboost propellant requirements for each sequence.
4. Movement of external equipment into pressurized nodes to reduce EVA time.
5. Movement of non-life-critical HAB module equipment into pressurized volume to provide health advantages to the crew.
6. Natural frequencies of the reference space station are not drastically affected with removal of the dual keel.

For each sequence and individual flight examined herein, additional latitude is available for other modifications to improve performance such as relaxing logistics requirements (e.g., global constraints like the 5-degree trim angle restriction), relocating payloads to improve mass balance, and refining the assembly altitudes. Undoubtedly, all these aspects will be

reexamined and refined as a part of the upcoming Phase C and D Space Station efforts.

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Table 1. CETF Options

Configuration	TRANSPORTATION		
	STS Only	STS + OMV	STS + OMV + ELV
Constrained Hardware (IOC)	1		1A
Polar Platform Reconfiguration	2		2 A
Large Module Connectors	3*	3A	3B

*Baseline Option

Table 2. Assembly Phasing of the Space Station
a) Sequence 1 (Baseline, Option 3)

FLIGHT			FLIGHT		
1	1/2 PV, Node, Truss		15	Logistics	
2	1/2 PV, Node, Truss		16	Serv. Fac., Payloads	← Phase 1 Service
3	TCS, Airlock, P/L, SSRMS		17	Logistics	
4	Airlock		18	Serv. Fac., Outfitt.	← Phase 2 Service
5	U.S. Lab Module	← Man-Tended	19	Logistics	
6	Lab Module Outfitting		20	JEM EF #2, ELM	
7	U.S. Hab Module		21	Logistics	
8	Nodes, Cupolas		22	MSC/Transporter	
9	Crew (4), Logistics	← PMC	23	Logistics	
10	SD Power	← SD	24	Logistics	
11	Logistics		25	Upper & Lower Booms	
12	JEM, EF #1		26	Logistics	
13	Logistics		27	Fac. Payloads	← Phase 3 Service IOC
14	ESA Module		28	Logistics	

Table 2. Assembly Phasing of the Space Station
b) Sequence 2 (Option 3B, Version 1)

Flight	
1	2 Nodes, Airlock
2	1/2 PV, Truss, 1/2 TCS, 1/2 RMS
3	1/2 PV, Truss, 1/2 TCS, 1/2 RMS
4 - 28	(Same as Sequence 1, Flights 4-28)

Table 2. Assembly Phasing of the Space Station
c) Sequence 3 (Option 3B, Version 3)

Flight		
1	OMV, 1/2 PV, Truss	
2	1/2 PV, Truss, TCS	
3	2 Nodes, Airlock, Cupola, Service Facility	
4	Lab Module	
5	2 Nodes, Lab Module Outfitting	← Man Tended
6	U. S. Hab Module	
7	Crew (4), Logistics	← PMC
8-26	(Same as Sequence 1 Flights 10-28)	

Table 2. Assembly Phasing of the Space Station
d) Sequence 4 (Option 4B, Version x)

Flight		
1	2 Nodes, Airlock	
2	OMV, 1/2 PV, Truss, 1/2 TCS	
3	1/2 PV, Truss, 1/2 TCS, Service Facility	
4	Lab Module	
5	2 Nodes, Cupola, Lab Module Outfitting	← Man Tended
6	U. S. Hab Module	
7	Crew (4), Logistics	← PMC
8-26	(Same as Sequence 1 Flights 10-28)	

Table 2. Assembly Phasing of the Space Station
e) Assembly Phasing (Option 3 Using OMV)

Flight	
1	OMV, 1/2 PV, Truss
2	1/2 PV, TCS
3	2 Nodes, Lab Module Outfitting
4	Lab Module ← Man Tended
5	U. S. Hab Module
6	2 Nodes, Cupola, RMS
7	Crew (2), Logistics, Airlock ← PMC
8-26	(Same as Sequence 1 Flights 10-28)

Table 3. Sequence 2 Mass and Inertia Properties of the Space Station

FLIGHT	Mass, kg x 10^3	Center of Mass, m			Inertia, kg-m^2					
		X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{xz}
1	14.512	N/A	N/A	N/A	3.32 E5	2.19 E4	3.32 E5	0	327	0
2	28.327	-1.19	17.1	-2.19	8.55 E6	1.18 E6	8.41 E6	-3.61 E5	9.12 E5	-6.94 E4
3	40.416	-1.58	1.19	-1.64	3.17 E7	1.99 E6	3.17 E7	4.74 E4	-1.23 E5	-1.01 E5

Table 4. Sequence 2 Attitude Control Requirements of the Space Station

Flight	Attitude (deg)			Peak Momentum Requirements, N-m-s	CMG's @ 3100 N-m-s	Peak Secular Momentum, N-m-s
	$\Psi(z)$	θ (y)	$\phi(x)$			
2	(-88.14)	(84.57)	(-93.21)	(3022)	(1)	(407.3)
3	3.57 (3.57)	5.0 (10.34)	0.43 (0.43)	2797 (2830)	1 (1)	1299 (1.174)

(   ) Fully Trimmed Condition to Minimize Secular Angular Momentum Build-Up

Table 5. Sequence 3 Mass and Inertia Properties of the Space Station

FLIGHT	Mass, kg x 10^3	Center of Mass, m			Inertia, kg-m^2					
		X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{xz}
1	18.027	-1.79	-38.4	-0.1	4.34 E6	8.7 E5	4.47 E6	-2.7 E5	-3.7 E4	-2.9 E4
2	34.732	-1.96	-9.1	-0.44	4.34 E7	1.74 E6	4.36 E7	-6.78 E5	-3 E4	-2.5 E3
3	50.953	-2.07	1.44	-0.52	3.12 E7	2.56 E6	3.11 E7	-4.1 E5	-3.5 E5	7.5 E5
5	82.042	-2.47	0.52	-2.41	3.23 E7	4.62 E6	3.32 E7	-2.7 E5	-1.5 E5	1.0 E6
7	113.369	-3.1	-1.12	-2.19	3.38 E7	5.88 E6	3.49 E7	4.98 E4	-6.75 E5	9.1 E5

Table 6. Sequence 3 Attitude Control Requirements of the Space Station

Flight	Attitude (deg)			Peak Momentum Requirements, N-m-s	CMG's @ 3100 N-m-s	Peak Secular Momentum, N-m-s
	$\Psi_{(z)}$	θ (y)	ϕ(x)			
1 (Arrow)	-90	-90	0	5864	2	5864
1	-90 (-91.83)	0 (-84.58)	-90 (-90.45)	5712 (6004)	2 (2)	5712 (781)
2 (Arrow)	-90	-90	0	12,850	5	12,850
2	-90 (-91.28)	0 (-0.91)	-90 (-91)	15,890 (1961)	6 (1)	15,890 (1939)
3	-0.27	-5	-1.83	5662	2	5662
5	-0.94	5	-2.22	4293	2	4293
7	(-0.85)	(-3.57)	(-3.91)	(10,330)	(4)	(508)

( ) Fully Trimmed Condition to Minimize Secular Angular Momentum Build-Up

Table 7. Sequence 4 Mass and Inertia Properties of the Space Staion

FLIGHT	Mass, kg x 10^3	Center of Mass, m			Inertia, kg-m^2					
		X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{xz}
2	30.325	-2.12	25.44	-0.18	1.20 E7	6.3 E5	1.19 E7	8.65 E5	3.49 E4	-1.17 E4
3	47.299	-1.5	1.89	-0.36	3.10 E7	1.8 E6	3.02 E7	-3.66 E5	5.91 E5	-2.43 E5
4	64.286	-3.02	1.43	-1.71	3.16 E7	2.75 E6	3.11 E7	-1.01 E4	7.18 E5	1.37 E5
6	87.881	-1.59	-1.05	-3.32	3.19 E7	3.66 E6	3.25 E7	-1.16 E5	6.32 E5	1.02 E5
7	103.635	-2.51	-1.78	-2.64	3.28 E7	4.84 E6	3.36 E7	2.27 E5	3.84 E5	-4.21 E5

Table 8. Sequence 4 Attitude Control Requirements of the Space Station

Flight	Attitude (deg)			Peak Momentum Requirements, N-m-s	CMG's @ 3100 N-m-s	Peak Secular Momentum, N-m-s
	$\Psi_{(z)}$	θ (y)	ϕ(x)			
2	(-89.57)	(-4.35)	(90.3)	(303)	(1)	(60.87)
3	3.07 (3.07)	5.0 (36.74)	-1.53 (-1.53)	4210 (3058)	2 (1)	4210 (68.8)
4	0.18 (0.18)	5.0 (40.14)	-2.44 (-2.44)	5932 (3228)	2 (2)	5932 (1.25)
6	1.47 (1.47)	5.0 (28.21)	-0.58 (-0.58)	11950 (4984)	4 (2)	11950 (1.45)
7	(0.1)	(-0.62)	(-2.47)	(7535)	(3)	(1.84)

( ) Fully Trimmed Condition to Minimize Secular Angular Momentum Build-Up

Table 9. Sequence 5 Mass and Inertia Properties of the Space Station

FLIGHT	Mass, kg x 10^3	Center of Mass, m			Inertia, kg-m^2					
		X	Y	Z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{yz}	I_{xz}
1	17.148	-0.09	-32.2	0.3	1.15 E7	7.87 E4	1.15 E7	-4.6 E4	2.1 E5	487
2	34.391	-1.75	-8.02	0.38	4.44 E7	1.12 E6	4.52 E7	-4.77 E5	2.19 E5	2.3 E4
3	50.059	-1.18	0.63	-0.45	3.23 E7	2.13 E6	3.22 E7	-1.16 E4	2.4 E5	-4.1 E4
4	67.046	-2.52	0.6	-1.6	3.28 E7	2.96 E6	3.3 E7	2.87 E5	2.47 E5	2.66 E5
5	81.639	-2.24	-0.56	-2.3	3.34 E7	3.16 E6	3.35 E7	1.57 E5	5.21 E5	1.84 E5
6	96.099	-1.31	-0.94	-2.68	3.38 E7	4.46 E6	3.48 E7	6.06 E5	6.38 E5	6.46 E5
7	112.463	-2.32	-1.44	-2.17	3.48 E7	5.8 E6	3.2 E7	4.32 E5	3.5 E5	-3.04 E5

Table 10. Sequence 5 Attitude Control Requirements of the Space Station

Flight	Attitude (deg)			Peak Momentum Requirements, N-m-s	CMG's @ 3100 N-m-s	Peak Secular Momentum, N-m-s
	$\Psi_{(z)}$	θ (y)	ϕ(x)			
1	(-1.66)	(4.5)	(-91.24)	(1251)	N/A	(507.8)
2	(6.5)	(0)	(-90.37)	(1265)	N/A	(384.5)
3	(0.59)	(-2.75)	(-0.98)	(2527)	(1)	(2.14)
7	(-3.68)	(3.38)	(-0.25)	(3909)	(2)	(3.52)

(   ) Fully Trimmed Condition to Minimize Secular Angular Momentum Build-Up

Table 11. Sequence 3 Orbital Decay Data

Flight (Launch Date)	Mass, kg x 10^3	Area, m^2	Ballistic Coeff, kg/m^2	Orbit Decay Time (Days)			Initial Altitude, Nmi for 90 Day Decay to [Rendezvous]
				220 Nmi-Rendezvous	180 Nmi-Rendezvous	0 Nmi-Rendezvous	
1 (1-1-93)	18.027	117	67	77	35	23	204 [150 Nmi]
2 (4-1-93)	34.732	203	74.4	198	51	29	194 [150 Nmi]
3 (7-1-93)	50.953	996	22.2	51	7	10	243 [150 Nmi]
5 (10-1-93)	82.042	1000	35.7	109	20	12	214 [150 Nmi]
7 (1-1-94)	113.364	1040	47.4	191	40	20	196 [150 Nmi]

Table 12. Sequence 4 Orbital Decay Data

Flight (Launch Date)	Mass, kg x 10^3	Area, m2	Ballistic Coeff, kg/m2	Orbit Decay Time (Days)			Initial Altitude, Nmi for 90 Day Decay to [Rendezvous]
				220 Nmi-Rendezvous	180 Nmi-Rendezvous	0 Nmi-Rendezvous	
2 (1-1-93)	30.325	180	73	183	43	22	197 [150 Nmi]
3 (4-1-93)	47.299	1030	20	50	10	11	241 [170 Nmi]
4 (7-1-93)	64.286	1030	27	63	7	22	231 [170 Nmi]
6 (10-1-93)	87.881	1030	37	96	N/A	30	219 [180 Nmi]
7 (1-1-94)	103.635	1030	44	104	N/A	81	217 [190 Nmi]

Table 13. Sequence 5 Orbital Decay Data

Flight (Launch Date)	Mass, kg x 10^3	Area, m^2	Ballistic Coeff, kg/m^2	Orbit Decay Time (Days)			Initial Altitude (Nmi) for 90 Day Decay to [Rendezvous]
				220 Nmi-Rendezvous	180 Nmi-Rendezvous	0 Nmi-Rendezvous	
1 (1-1-93)	17.148	99.8	74.7	125	26	21	210 [150 Nmi]
2 (4-1-93)	34.391	170	88	225	N/A	137	203 [190 Nmi]
3 (7-1-93)	50.059	988	22	30	N/A	33	251 [190 Nmi]
7 (7-1-93)	112.463	1050	46.6	160	N/A	87	208 [190 Nmi]

Table 14. Candidate External Equipment That May Be Moved To Pressurized Volume

Equipment		Wt, kg	Vol, m3	Vol, including packaging, m3	Power, kW
C&T	C&M controllers, base BD, sig proc, power supplies	357.4	0.27	0.91	0.500
DMS	MSU, processors, bridges, NIU	273.9	0.31	1.04	0.150
FMAD	Elect. cont units, MDM	136.1	0.15	0.51	0.500
GN&C	Processors, RCS elect.	114.3	0.14	0.45	0.100
HR&T	Rotary joint cont system, MDM, processor	155.1	0.15	0.51	0.680(1)
EPS	Controller	45.4(2)	0.05(2)	0.05(2)	0.200(2)
Struct/Mech	Alpha joint control system, MDM	105.2	0.09	0.30	0.100
Total		1187.4	1.17	3.77	2.230

Notes: (1) - Data Obtained form JSC (Chin Lin)
(2) - Data Obtained from LeRC (Steve Winegar)
All Other Data Obtained from Resource Group
Weight & Volume Data Except as Noted Obtained from McDonnell Douglas

Table 15. External Equipment Moved to Node 3

Rack	Equipment	Qty	Wt, kg	Vol, m3	Power, kW
1	C & T	1	357.4	0.91	0.500
	GN&C	1	114.3	0.45	0.100
	Total	2	471.7	1.36	0.600
2	DMS	1	273.9	1.04	0.150
	Struct/Mech	1	105.2	0.30	0.100
	Total	2	379.1	1.34	0.250
3	FMAD	1	136.1	0.51	0.500
	HR&T	1	155.1	0.51	0.680
	EPS	1	45.4	0.05	0.200
	Total	3	336.6	1.07	1.380

Table 16. Candidate HAB Module Equipment That May Be Moved To Nodes

Equipment	Qty	Wt, kg	Vol (m^3), includes 15% for packaging	Vol (m^3), includes 26.4% for packaging	Power, kW
EPS (Control)	1	45.4 (1)	0.05 (1)	0.05 (1)	0.2 (1)
Urine Collection	1	28.7	0.12	0.13	0.1584
Urine Processing	2	210.9	0.64	0.70	0.1056
Urine Processing Controller	2	43.5	0.42	0.46	0.008
Fecal Collection & Processing	1	105.2	0.93	1.02	0.24
Trash Collection & Processing	1	109.5	0.62	0.68	0.137
Gen Housekeeping (Wipe, Vacuum Cleaner)	1	52.9	0.18	0.20	0.0
Hygiene Water Processing	1	214.7	0.51	0.56	0.0594
Hygiene Water Processing Controller	1	2.7	0.01	0.01	0.01
Water Thermal Conditioning	1	13.3	0.08	0.08	0.4875
Common Module Service (Shower, Handwash)	1	147.8	1.67	1.83	0.0037
Total	13	974.6	5.23	5.72	1.4096

Note: (1) - Data Obtained from LeRC (Steve Winegar)
All Other Data Obtained from MSFC

Table 17. HAB Module Equipment Moved to Node 4

Rack	Equipment	Qty	Wt, kg	Vol, m3	Power, kW
1	Urine Collection	1	28.7	0.12	0.1584
	Urine Processing	2	210.9	0.70	0.1056
	Urine Processing Controller	2	43.5	0.46	0.0080
	Total	5	283.1	1.28	0.2720
2	EPS (CONTROL)	1	45.4	0.05	0.20
	Fecal Collection & Processing	1	105.2	1.02	0.24
	Total	2	150.6	1.07	0.44
3	Trash Collection & Processing	1	109.5	0.68	0.137
	Gen Housekeeping (Wipe, Vacuum Cleaner)	1	52.9	0.20	0.000
	Total	2	162.4	0.88	0.137

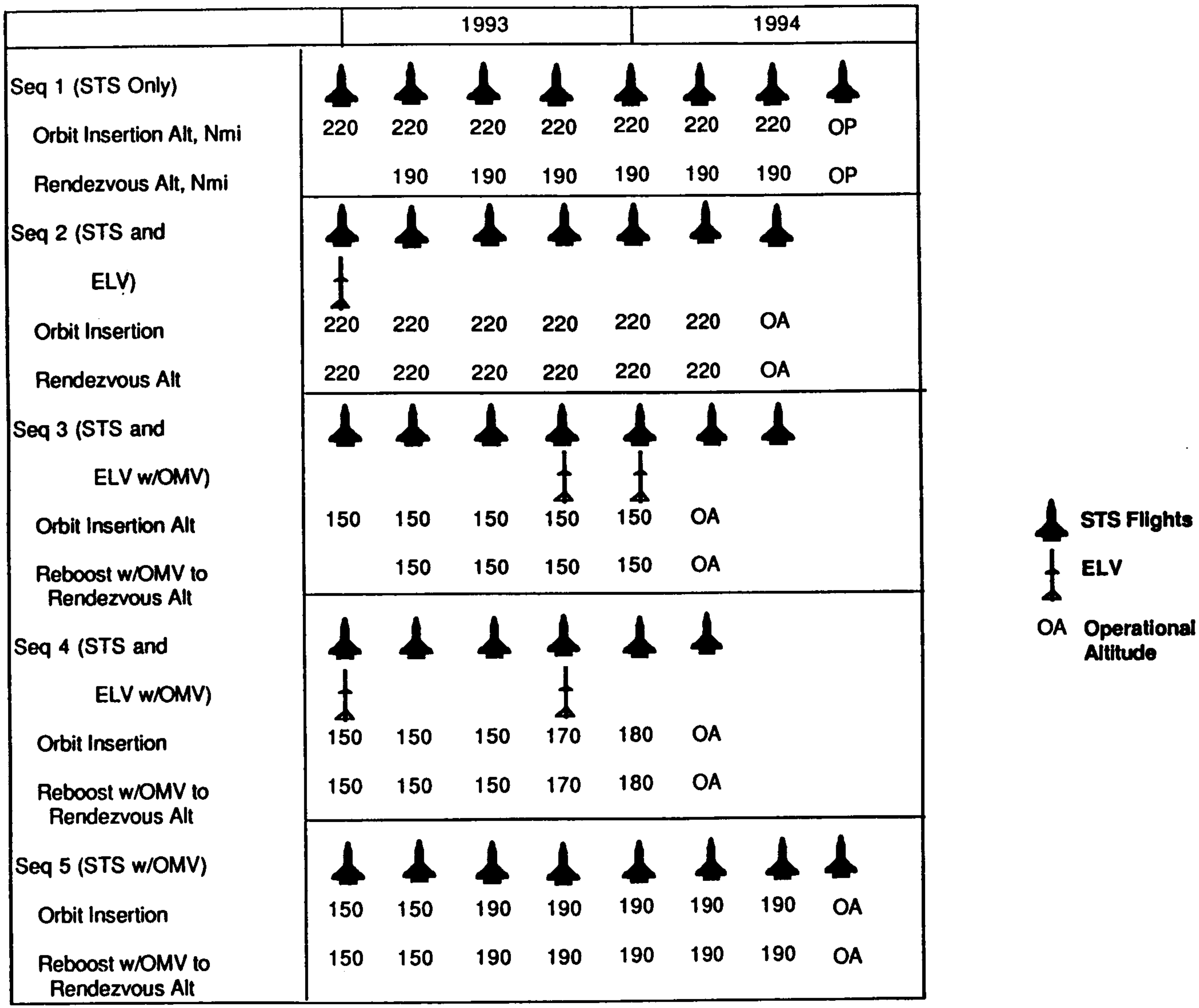


Figure 1. Flight Timetable for Five Assembly Sequences

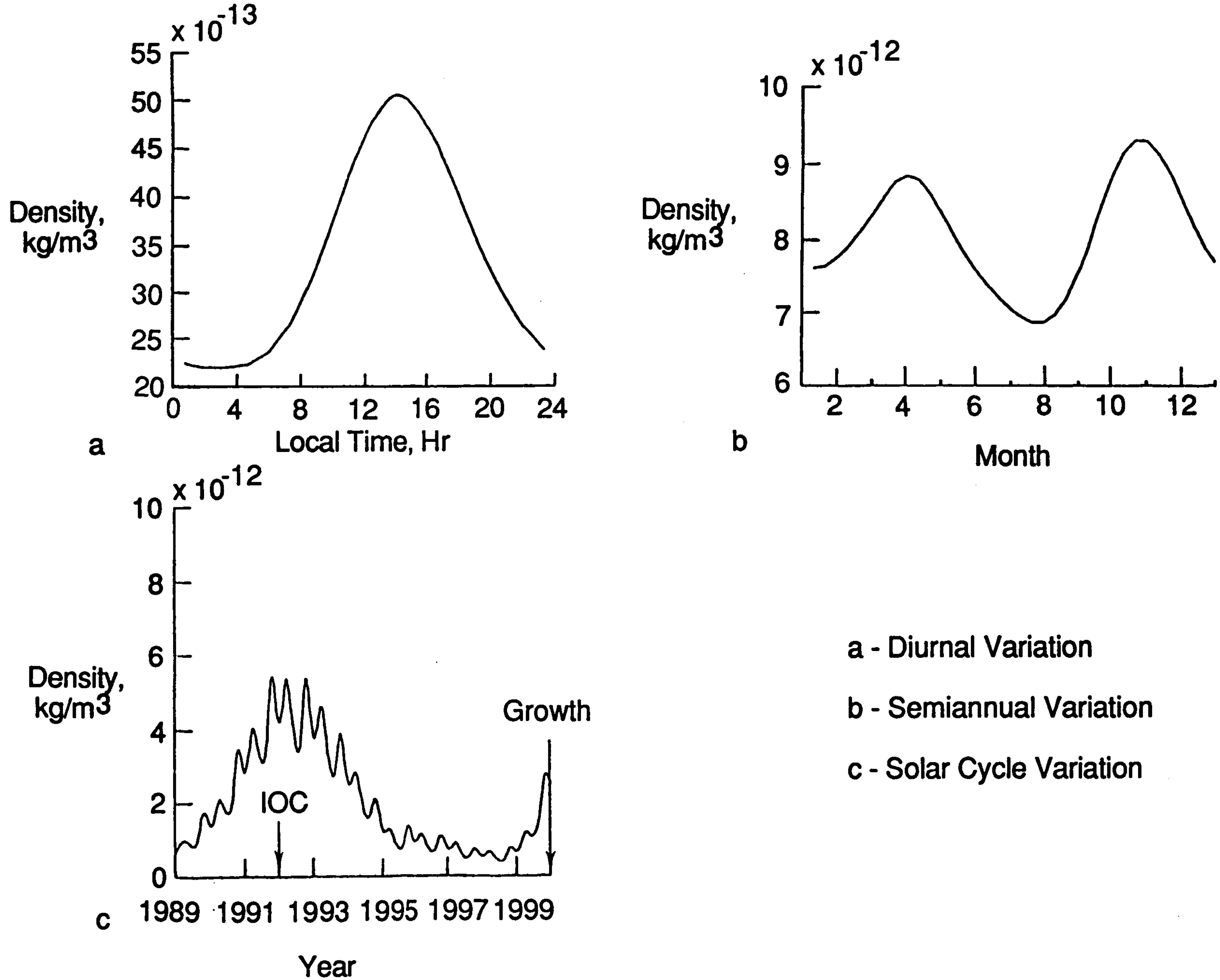


Figure 2. Density Variations of 2 sigma Jacchia Atmosphere (Ref. 3)

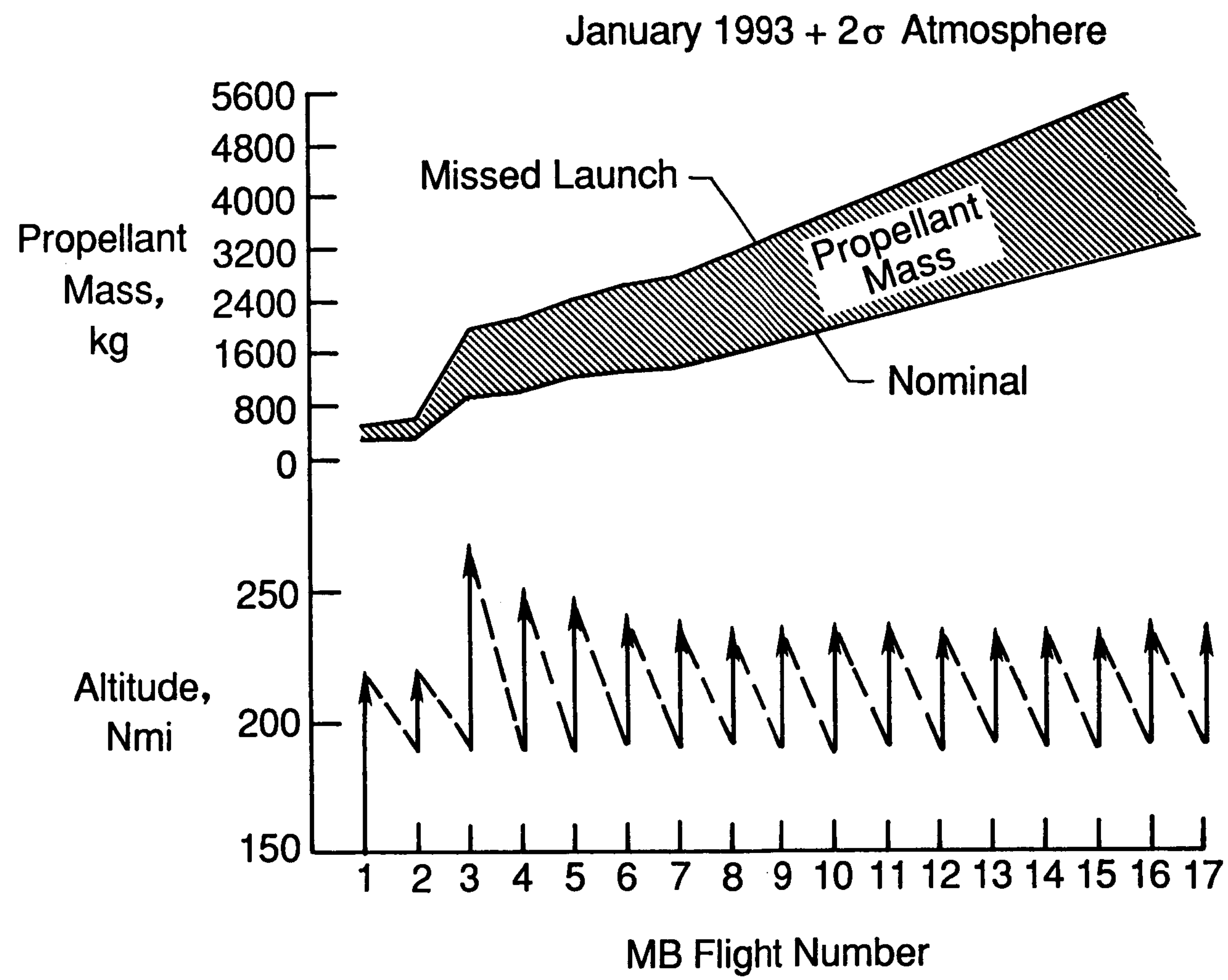


Figure 3. Option 3 Reboost Altitude and Propellant Requirements (For 90-Day Decay Back to 190 Nmi)

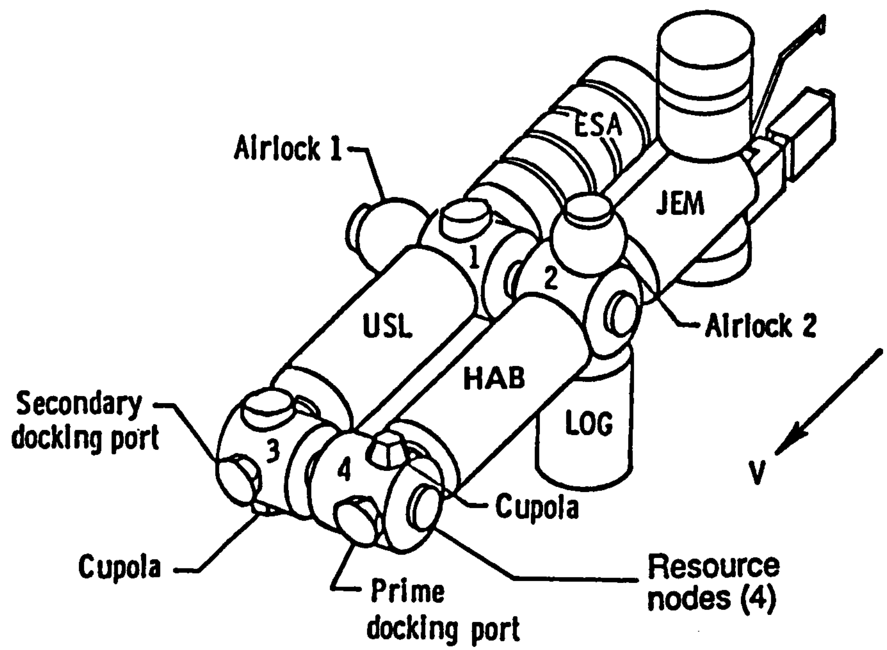


Figure 4. Space Station Configuration Showing Connecting Node Locations

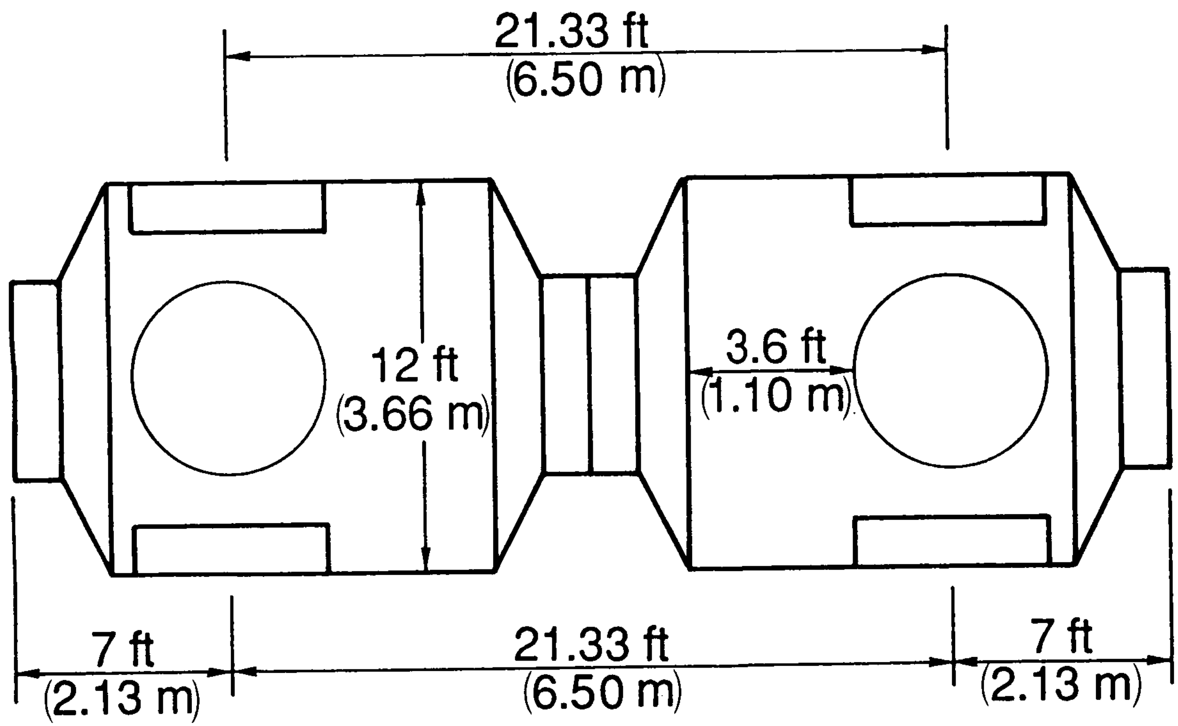


Figure 5. Nodes Configuration

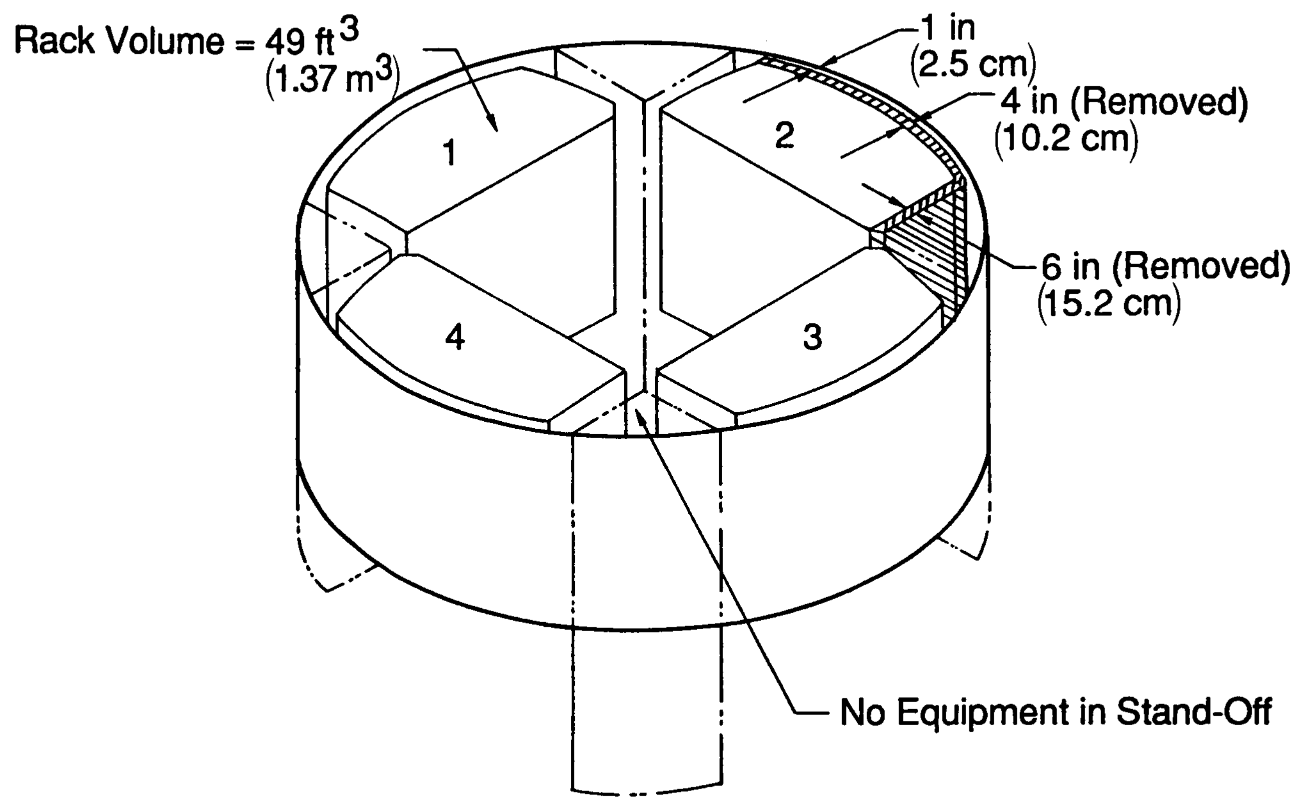


Figure 6. Equipment Rack Configuration (Two in each node)

(5-m Bays)

EI = 1.848×10^9 N-m^2
EA = 3.737×10^8 N
Gj = 4.492×10^8 N-m^2

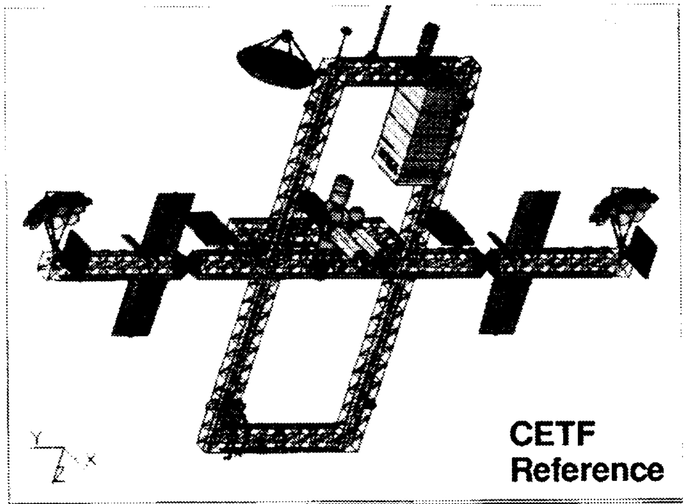
CETF Reference

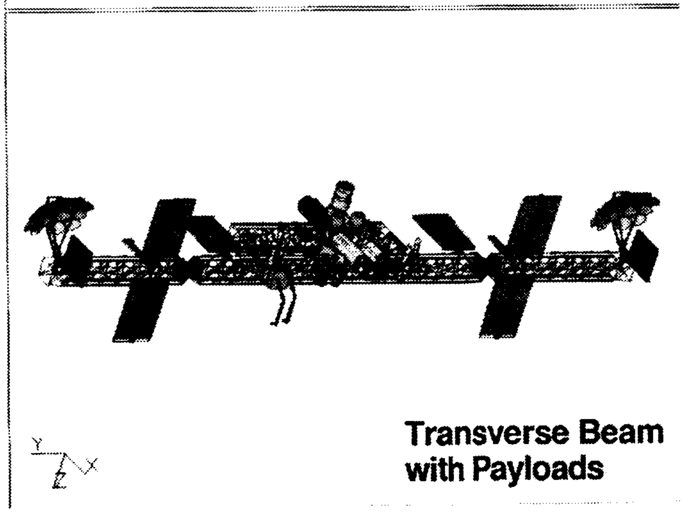
Frequency (Hz)	Description
0.237	Transverse Boom Bending
0.243	Transverse Boom Bending
0.308	Transverse Boom Twist
0.321	Keel Twist
0.348	Transverse Boom/Keel Twist
0.424	Keel Twist

(5-m Bays)

CETF Without Keel

Frequency (Hz)	Description
0.232	Transverse Boom Bending
0.243	Transverse Boom Bending
0.471	Transverse Boom Twist
0.589	Transverse Boom Twist
0.695	Transverse Boom Bending
0.748	Transverse Boom Twist





(9-ft Bays)

EI = 4.075×10^8 N-m^2
EA = 2.744×10^8 N
Gj = 9.930×10^7 N-m^2

CETF Reference

Frequency (Hz)	Description
0.116	Transverse Boom Bending
0.121	Transverse Boom Bending
0.148	Transverse Boom Twist
0.158	Keel Twist
0.169	Keel Bending/Twist
0.205	Transverse Boom/Keel Twist

(9-ft Bays)

CETF Without Keel

Frequency (Hz)	Description
0.111	Transverse Boom Bending
0.119	Transverse Boom Bending
0.225	Transverse Boom Twist
0.281	Transverse Boom Twist
0.333	Transverse Boom Bending
0.360	Transverse Boom Twist

Figure 7. Two Space Station Structural Concepts

APPENDIX A

The launch manifests for sequences 2 through 5 are presented in this appendix with the payload description (components and mass) for each flight. A brief description of the tasks to be performed during rendezvous is included.

Flight Manifest

Sequence 2 (Option 3B, Version 1)

Flight 1/ELV-1	Mass lb.	Mass kg.
Aft port large node	9,660	4,386
Aft starboard large node	9,449	4,290
Airlock	6,811	3,092
Docking adaptor	1,100	499
CMG package	3,464	1,573
FSE & margin	1,516	688
TOTAL	32,000	14,528

ELV TITAN 4 (220-nmi circular orbit)

Flight Activity:

Payload will be parked in a 220-nmi orbit for rendezvous with flight 2/STS-1. The equipment will be stored/attached to the transverse boom which will be assembled on flight 2.

Flight 2/STS-1

	Mass lb.	Mass kg.
Pressurized module	10,798	4,902
Starboard transverse boom (10 bays)	1,679	762
Utilities (7 bays)	4,319	1,961
Starboard radiator	4,407	2,001
RMS attach structure	350	159
3 RCS modules	6,315	2,867
Antennas and antenna package	545	247
FSE & margin	5,352	2,430
TOTAL	33,765	15,329

STS (220-nmi circular orbit)

Flight Activity:

Dock with flight 1 payload via docking device. Assemble starboard transverse boom - start with the pressurized module equipment bay and work toward what will be the center of the station, attaching equipment at appropriate points during the assembly process. Connect and configure flight 1 payload to transverse boom. Attach STS RMS arm to station.

Flight 3/STS-2

	Mass lb.	Mass kg.
Pressurized module	10,798	4,902
Port transverse boom 10 bays	1,169	531
Utilities 10 bays	6,170	2,800
Port radiator	4,407	2,001
RMS attach structure	350	159
1 RCS module	2,105	956
FMAD tankage	5,735	2,603
FSE & margin	3,032	1,377
TOTAL	33,766	15,330

STS (220-nmi circular orbit)

Flight Activity:

Dock with station via docking device. Assemble port transverse boom - resume construction and work toward port pressurized module, attaching equipment at appropriate points during the assembly process. Attach STS RMS arm to station.

Flight 4 onward (same as Option 3)

Flight Manifest

Sequence 3 (Option 3B, Version 3)

Flight 1/STS-1

	Mass lb.	Mass kg.
OMV (fully loaded)	12,700	5,765
Pressurized module	10,772	4,890
Starboard transverse boom	1,932	877
2 RCS modules	4,210	1,911
PMAD	1,304	592
DMS	204	93
C&T	296	134
RCS radiator assembly	3,211	1,458
TCS	2,946	1,337
SIA	409	186
FSE & margin	4,916	2,232
TOTAL	42,900	19,476

STS (150-nmi circular orbit)

Flight activity:

Assemble starboard transverse boom - start with pressurized module equipment bay and work toward what will be the center of the station, attaching equipment at appropriate points during the assembly process. OMV will be attached to the end of the transverse boom by the pressurized module. Reboost station so that next flight rendezvous will be at 150 nmi.

Flight 2/STS-2

	Mass lb.	Mass kg.
Pressurized module	10,772	4,890
Port transverse boom	2,208	1,002
2 RCS modules	4,210	1,911
PMAD	1,368	621
DMS	247	112
C&T	296	134
TCS radiator assembly	3,211	1,458
TCS	3,945	1,791
6 CMG's	3,474	1,577
External GN&C equipment	236	107
SIA	409	187
PIA	1,060	481
Payload	4,000	1,816
FSE & margin	5,194	2,359
TOTAL	40,630	18,446

STS (150-nmi circular orbit)

Flight activity:

Dock with station (flight 1) via docking device. Assemble port transverse boom - resume construction and work toward the port pressurized module, attaching equipment at appropriate points during the assembly process. Reboost station to 150-nmi plus 90-days altitude.

Flight 3/STS-3

	Mass lb.	Mass kg.
Aft starboard large node	9,449	4,290
Aft port large node	9,660	4,386
2 docking adaptors	2,200	999
Servicing facility hardware w/OMV accommodations	8,575	3,893
Standard airlock	4,430	2,011
Cupola	1,600	726
FSE & margin	6,916	3,140
TOTAL	42,830	19,445

STS (150-nmi circular orbit)

Flight Activity:

Dock with station. Attach payload equipment to appropriate points on the station. Reboost station to 150-nmi plus 90-days altitude.

Flight 4/ELV-1

	Mass lb.	Mass kg.
Lab module minus offloads	34,000	15,436
FSE & margin	1,000	454
TOTAL	35,000	15,890

Titan 4 (150-nmi circular orbit)

Flight activity:

OMV retrieves flight 4 package and docks with the station.

Flight 5/STS-4

	Mass lb.	Mass kg.
Forward starboard node	8,750	3,973
Forward port node	8,750	3,973
CERV	6,000	2,724
Lab module offloads	11,000	4,993
FSE & margin	6,130	2,783
TOTAL	40,630	18,446

STS (150-nmi circular orbit)

Flight Activity:

Dock with station. Attach equipment from flights 4 and 5 to the station at the appropriate points. Install lab module offloads. Reboost to 150-nmi plus 90-days altitude. Station is now in a man-tended condition.

Flight 6/ELV-2

	Mass lb.	kg.
HAB module minus offloads	34,000	15,436
FSE & margin	1,000	454
TOTAL	35,000	15,890

Titan 4 (150-nmi circular orbit)

Flight activity:

OMV retrieves and docks with station.

Flight 7/STS-5

	Mass lb.	kg.
Crew of 4	1,800	817
Log module	15,800	7,173
90-day supply	10,280	4,667
Skip cycle supply	5,610	2,547
HAB module outfitting	1,500	681
FSE & margin	5,640	2,561
TOTAL	40,630	18,446

STS (150-nmi circular orbit)

Flight activity:

Dock with station. Attach payloads from flights 6 and 7 to station. Transfer crew. Final checkout of station function before STS leaves. Reboost to operational altitude. Station is permanently manned.

Flight Manifest

Sequence 4 (Option 3B, Version X)

Flight 1/ELV-1	Mass lb.	Mass kg.
Aft port large node	9,600	4,386
Aft starboard large node	9,449	4,290
Airlock	4,430	2,011
2 docking adapters	2,200	999
OMV (smart section)	4,500	2,043
FSE & margin	4,536	2,059
TOTAL	34,775	15,788

ELV Titan 4 (150-nmi circular orbit)

Flight activity:

Payload will be parked in a 150-nmi orbit for rendezvous with flight 2. The equipment will be stored attached to the transverse boom. The transverse boom will be assembled on flight 2. The smart section of the OMV will be used for attitude control of the payload once released from the Titan.

Flight 2/STS-1

	Mass lb.	Mass kg.
OMV (remaining)	8,200	3,723
OMV accommodations	500	227
Pressurized module	10,720	4,867
Starboard transverse boom and associated masses	4,971	2,257
Starboard radiator	2,188	993
SIA	409	186
PIA	1,060	481
GN&C	3,760	1,707
Lower boom antennas	607	276
Upper boom antennas	607	276
FSE & margin	6,619	3,005
TOTAL	39,641	17,998

STS (150-nmi circular orbit)

Flight activity:

Dock with flight 1 payload via docking device. Assemble starboard transverse boom - start with the pressurized module equipment bay and work toward what will be the center of the station, attaching equipment at appropriate points during the assembly process. OMV will be attached to the end of the transverse boom by the pressurized module. Reboost station so that next flight rendezvous will be at 150 nmi.

Flight 3/STS-2

	Mass lb.	Mass kg.
Pressurized module	10,772	4,890
Port transverse boom and associated masses	6,200	2,815
Port radiator	1,167	530
4 RCS modules	8,420	3,823
Servicing facility hardware and misc. payloads	7,180	3,260
FSE & margin	3,374	1,532
TOTAL	37,113	16,849

STS (150-nmi circular orbit)

Flight activity:

Dock with station via docking device. Assemble port transverse boom - resume construction and work toward the port pressurized module, attaching equipment and flight 1 hardware at appropriate points during the assembly process. Reboost station to 150-nmi plus 90-days altitude.

Flight 4/STS-3

	Mass lb.	Mass kg.
Lab module minus offloads	37,457	17,006
FSE & margin	1,873	850
TOTAL	39,330	17,856

STS (150-nmi circular orbit)

Flight Activity:

Dock with station and attach LAB module to the station. Reboost to 170-nmi plus 90 days altitude.

Flight 5/ELV-2

	Mass lb.	Mass kg.
2 forward nodes	17,500	7,945
CERV	6,000	2,724
Cupola	1,600	726
Lab module offloads	4,075	1,850
FSE & margin	4,376	1,987
TOTAL	33,551	15,232

ELV Titan 4 (170-nmi circular orbit)

Flight activity:

OMV retrieves flight 5 package and docks with the station.

Flight 6/STS-4

	Mass lb.	Mass kg.
HAB Module minus offloads	35,552	16,141
FSE & margin	1,778	807
TOTAL	37,330	16,948

STS (170-nmi circular orbit)

Flight activity:

Dock with station and attach HAB module to the station. Attach payload from flight 5 to appropriate points. Install LAB module offloads. STS brings OMV back to ground for servicing. Reboost to 180-nmi plus 90-days altitude.

Flight 7/STS-5

	Mass lb.	Mass kg.
Crew (4 members)	1,800	817
90-day supply	10,280	4,667
Skip cycle supply	5,610	2,547
Misc. user payload	2,983	1354
Logistics module	12,264	5,568
FSE & margin	3,294	1,495
TOTAL	36,231	16,448

STS (180-nmi circular orbit)

Flight activity:

Dock with station. Attach payload to station. Transfer crew. Final checkout of station function before STS leaves. Reboost to operational altitude. Station is permanently manned.

Flight Manifest

Sequence 5 (Option 3 Using OMV)

Flight 1/STS-1

	Mass lb.	Mass kg.
OMV (fully loaded)	12,722	5,776
Pressurized module	12,910	5,861
Starboard transverse boom	4,928	2,237
Port transverse boom	4,651	2,112
Erector set	3,000	1,362
Docking adaptor	1,100	499
FSE & margin	4,317	1,961
TOTAL	43,630	19,808

STS (150-nmi circular orbit)

Flight activity:

Assemble starboard and port transverse booms - start with the pressurized module equipment bay and work toward what will be the center of the station and then toward the end where the other pressurized module (brought up on the following flight) will be attached, attaching equipment at appropriate points during the assembly process. OMV will be attached to the end of the transverse boom by the pressurized module. Reboost station so that next flight rendezvous will be at 150 nmi.

Flight 2/STS-2

	Mass lb.	Mass kg.
Pressurized module	12,910	5,861
Port radiator & HR & T	4,274	1,940
Starboard radiator & HR & T	4,502	2,044
Antennas (2 pods)	250	114
Little red wagon	6,000	2,724
4 RCS modules	9,556	4,338
Stringer & resisto jet	866	393
FSE & margin	2,268	1,030
TOTAL	40,626	18,444

STS (150-nmi circular orbit)

Flight activity:

Dock with station (flight 1) via docking devices. Attach pressurized module to structure of flight 1. Attach other equipment at appropriate points on structure. Reboost station to 190-nmi plus 90-days altitude.

Flight 3/STS-3

	Mass lb.	kg.
Aft starboard large node	7,344	3,334
Aft port large node	11,650	5,289
GN&C	4,274	1,940
Antennas	1,037	471
Lab module offloads	4,000	1,816
Docking adaptor	1,100	499
Servicing facility hardware	1,850	840
FSE & margin	5,375	2,440
TOTAL	36,630	16,630

STS (190-nmi circular orbit)

Flight activity:

Dock with station. Attach payload equipment to appropriate points on the station. Reboost station to 190-nmi plus 90-days altitude.

Flight 4/STS-4

	Mass lb.	kg.
LAB module minus offloads	34,000	15,436
FSE & margin	1,000	454
TOTAL	35,000	15,890

STS (190-nmi circular orbit)

Flight activity:

Dock with station and attacn LAB module to the station. Reboost to 190-nmi plus 90-days altitude.

Flight 5/STS-5

	Mass lb.	kg.
HAB module	34,000	15,436
FSE & margin	1,000	454
TOTAL	35,000	15,890

STS (190-nmi circular orbit)

Flight activity:

Dock with station and attach HAB module to the station. Reboost to 190-nmi plus 90-days altitude.

Flight 6/STS-6

	Mass lb.	kg.
2 forward nodes	22,068	10,019
CERV	6,000	2,724
Cupola	1,600	726
Structures & arm	2,200	999
FSE & margin	4,762	2,162
TOTAL	36,630	16,630

STS (190-nmi circular orbit)

Flight activity:

Dock with station. Attach equipment to the station at the appropriate points. Reboost to 190-nmi plus 90-days altitude.

Flight 7/STS-7

	Mass lb.	Mass Kg.
2 crew (other 2 crewmen will be part of 5 person flight crew; only 3 people return from flight this time.)	900	409
LOG module	11,452	5,199
90-day supply	10,280	4,667
Skip cycle supply	5,610	2,547
Airlock	4,430	2,011
FSE & margin	2,658	1,207
TOTAL	35,330	16,040

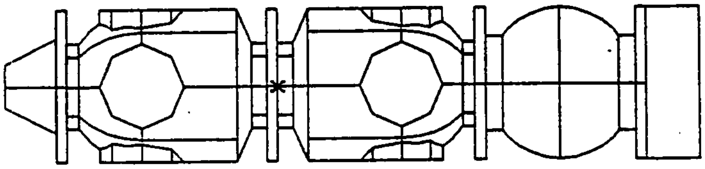
STS (190-nmi circular orbit)

Flight activity:

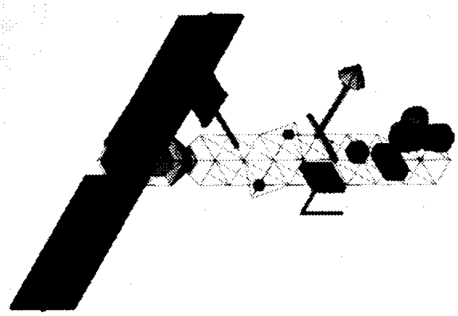
Dock with station. Attach payload to station. Transfer crew. Final checkout of station function before STS leaves. Reboost to operational altitude. Station is permanently manned.

APPENDIX B

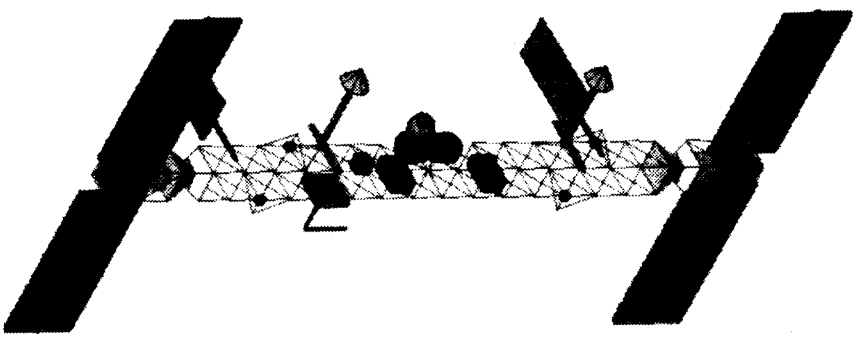
Appendix B presents figures of the assembly sequences for the four versions of Option 3 that were examined in the study (sequences 2-5). The ELV flights are not shown, with the exception of flight 1, sequence 2 (Option 3B, Version 1), which is presented to illustrate the type of payload configuration to be carried on the ELV.



(a) ELV Payload Configuration

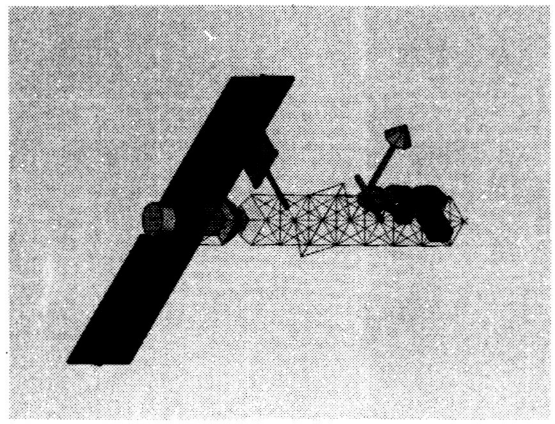


(b) System after Flight 2

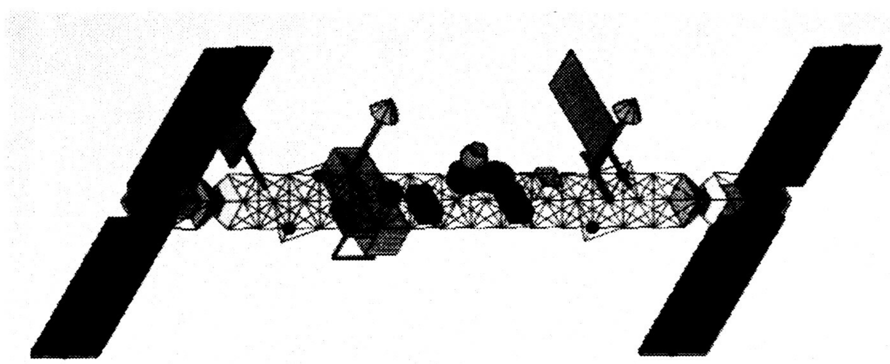


(c) System after Flight 3

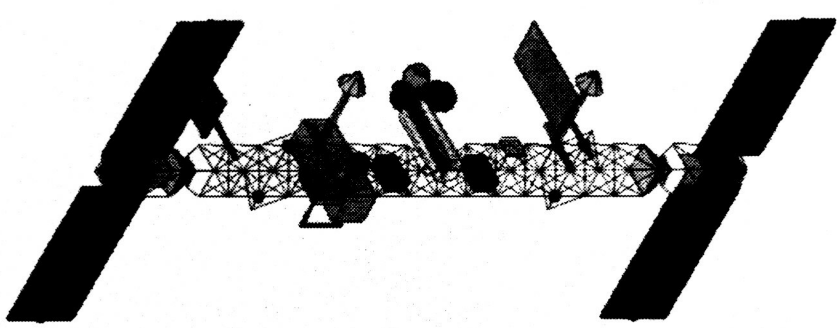
Figure B1. Assembly Sequence 2



(a) System after Flight 2

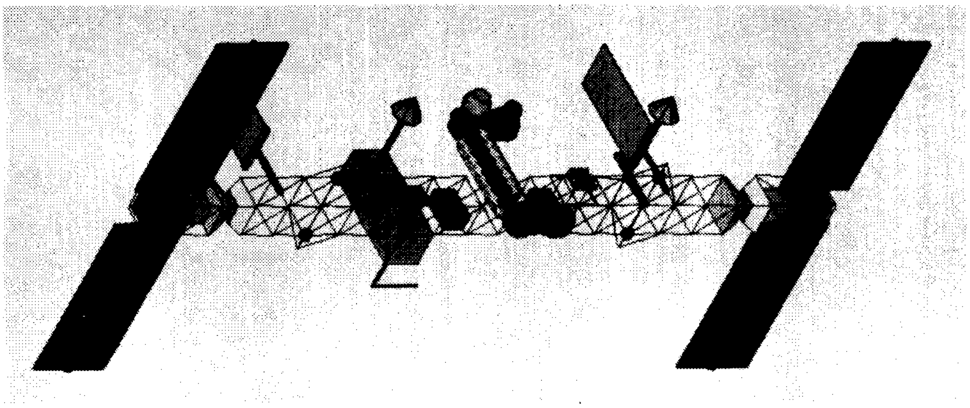


(b) System after Flight 3

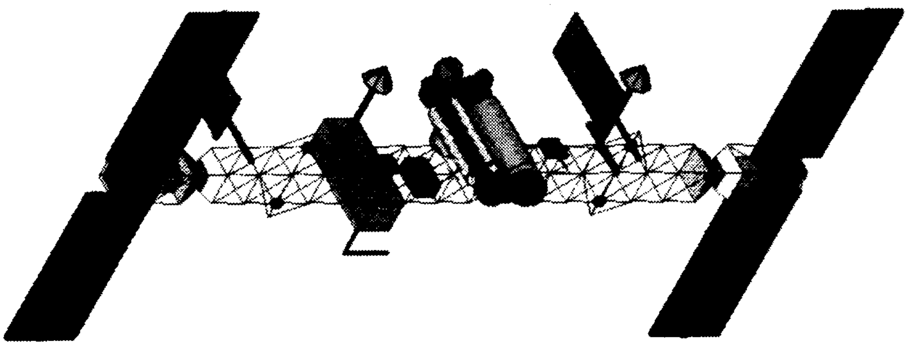


(c) System after Flight 4

Figure B3. Assembly Sequence 4

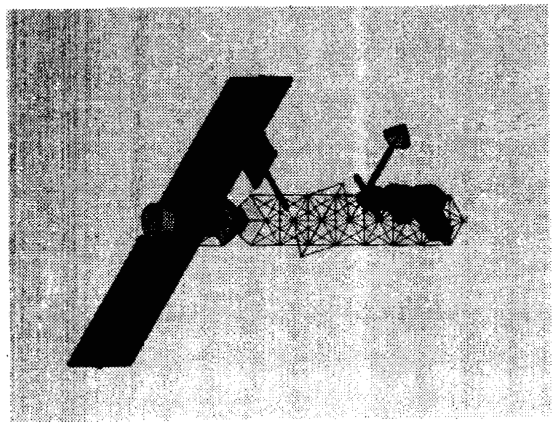


(d) System after Flight 5

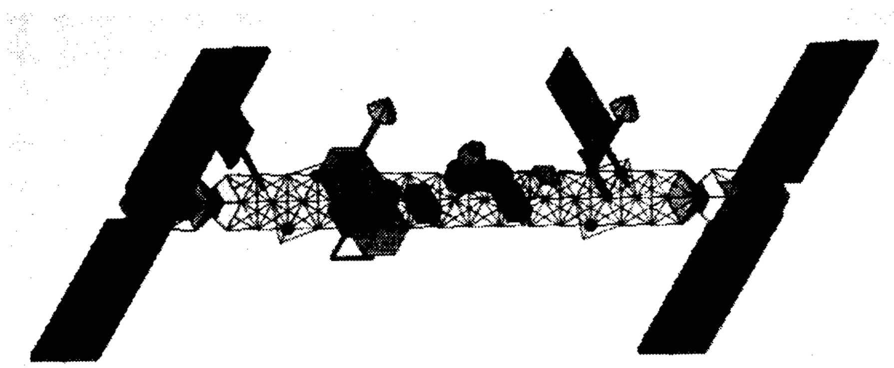


(e) System after Flight 7

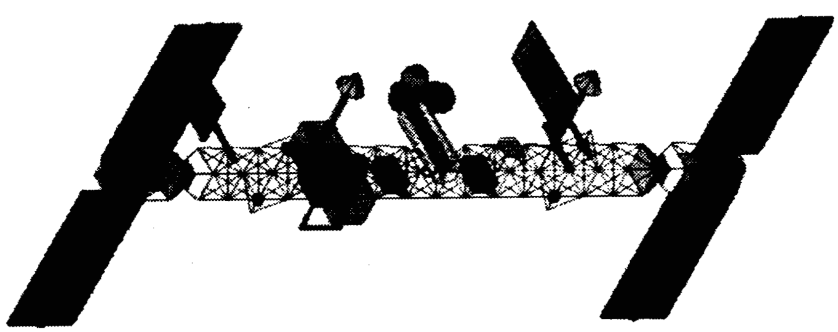
Figure B2. Assembly Sequence 3 (Concluded)



(a) System after Flight 2

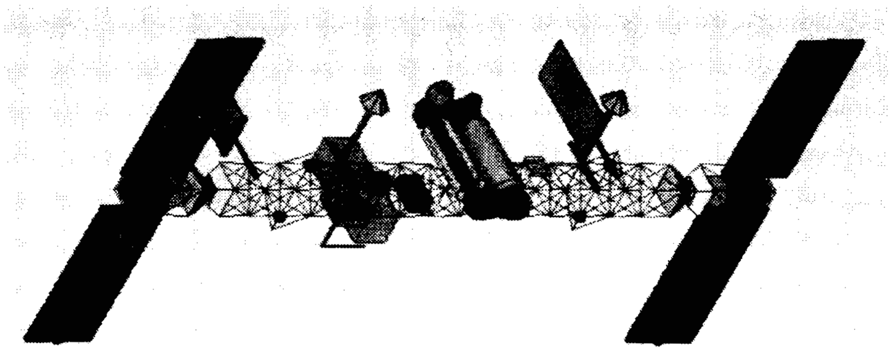


(b) System after Flight 3

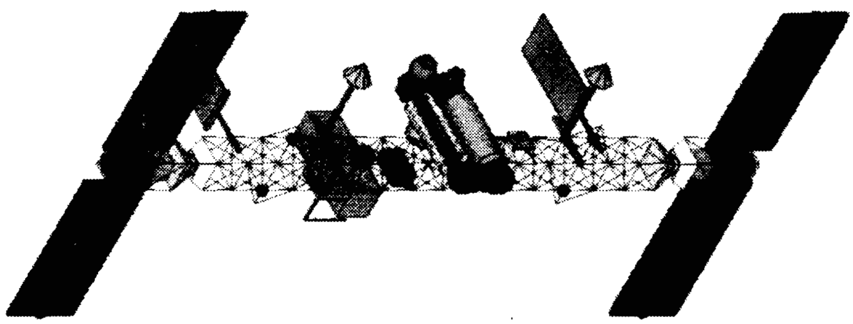


(c) System after Flight 4

Figure B3. Assembly Sequence 4

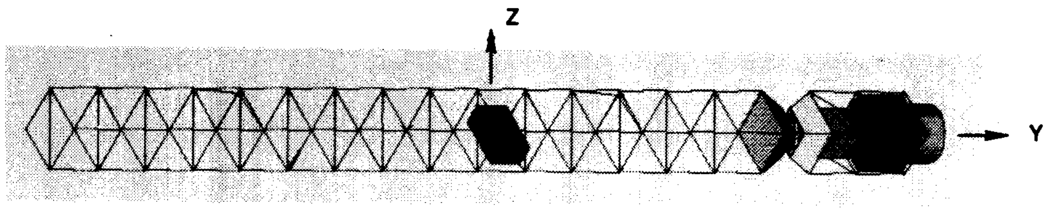


(d) System after Flight 6

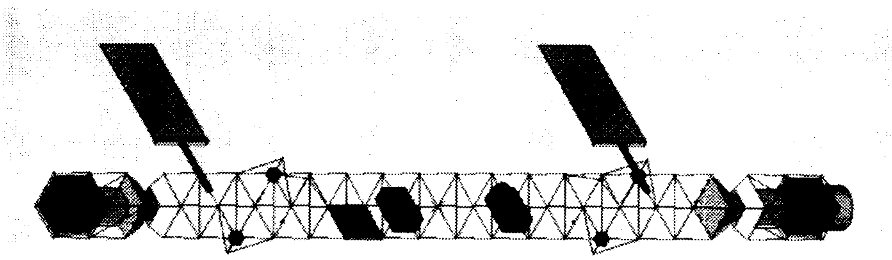


(e) System after Flight 7

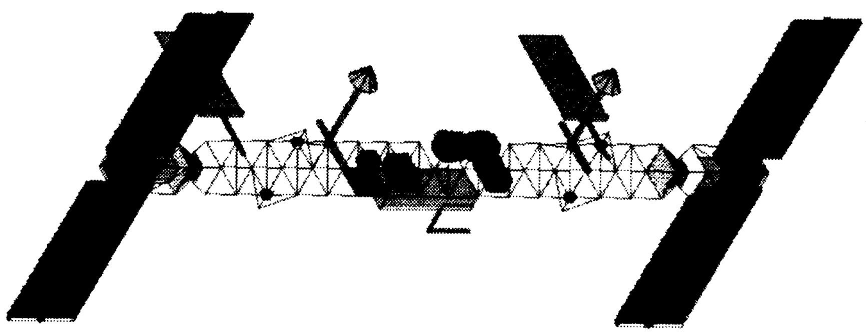
Figure B3. Assembly Sequence 4 (Concluded)



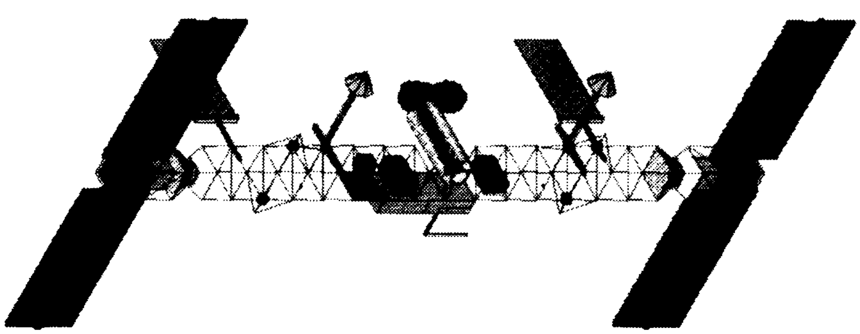
(a) System after Flight 1



(b) System after Flight 2

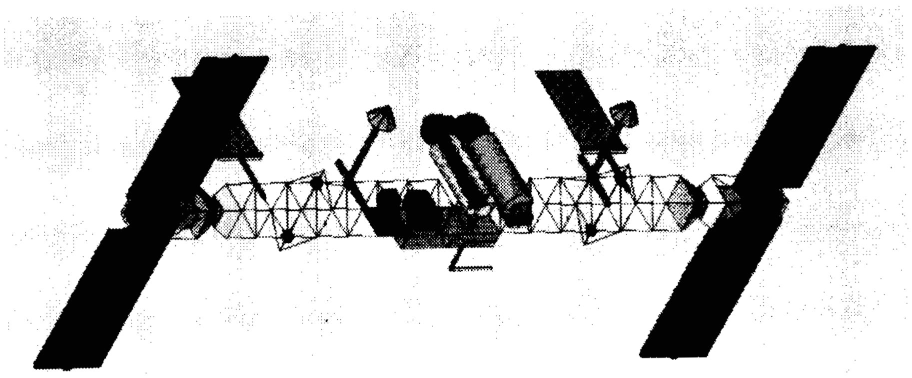


(c) System after Flight 3

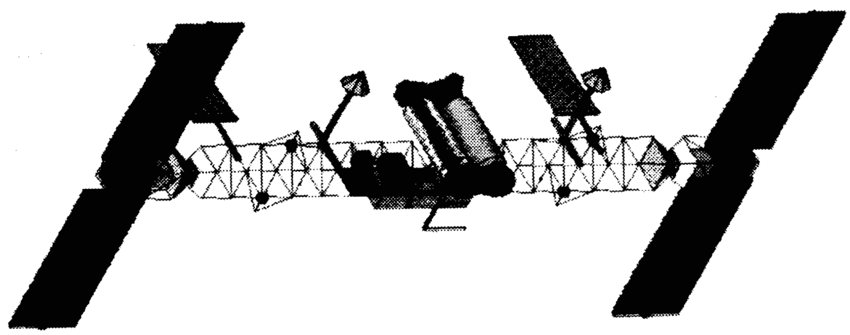


(d) System after Flight 4

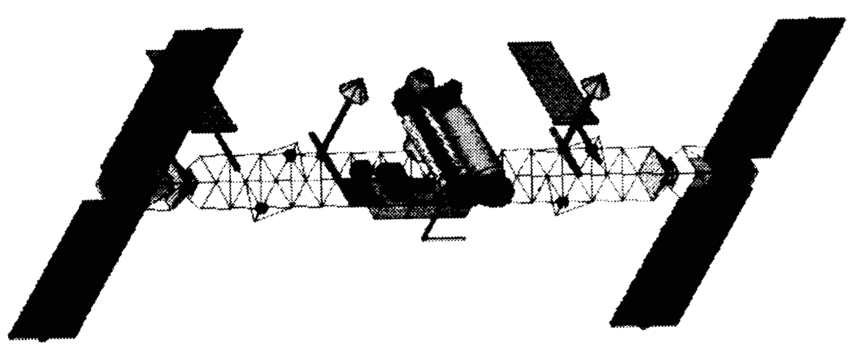
Figure B4. Assembly Sequence 5



(e) System after Flight 5



(f) System after Flight 6



(g) System after Flight 7

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Figure B4. Assembly Sequence 5 (Concluded)

APPENDIX C

Appendix C presents the orbital decay profiles for various initial altitudes and ballistic coefficients. The altitudes range from 150 to 250 nmi with ballistic coefficients of 20, 50, and 100 kg/m^2. Profiles were generated for both a nominal and a 2-sigma atmosphere. The date used for the initial altitude for all profiles is January 15, 1993.

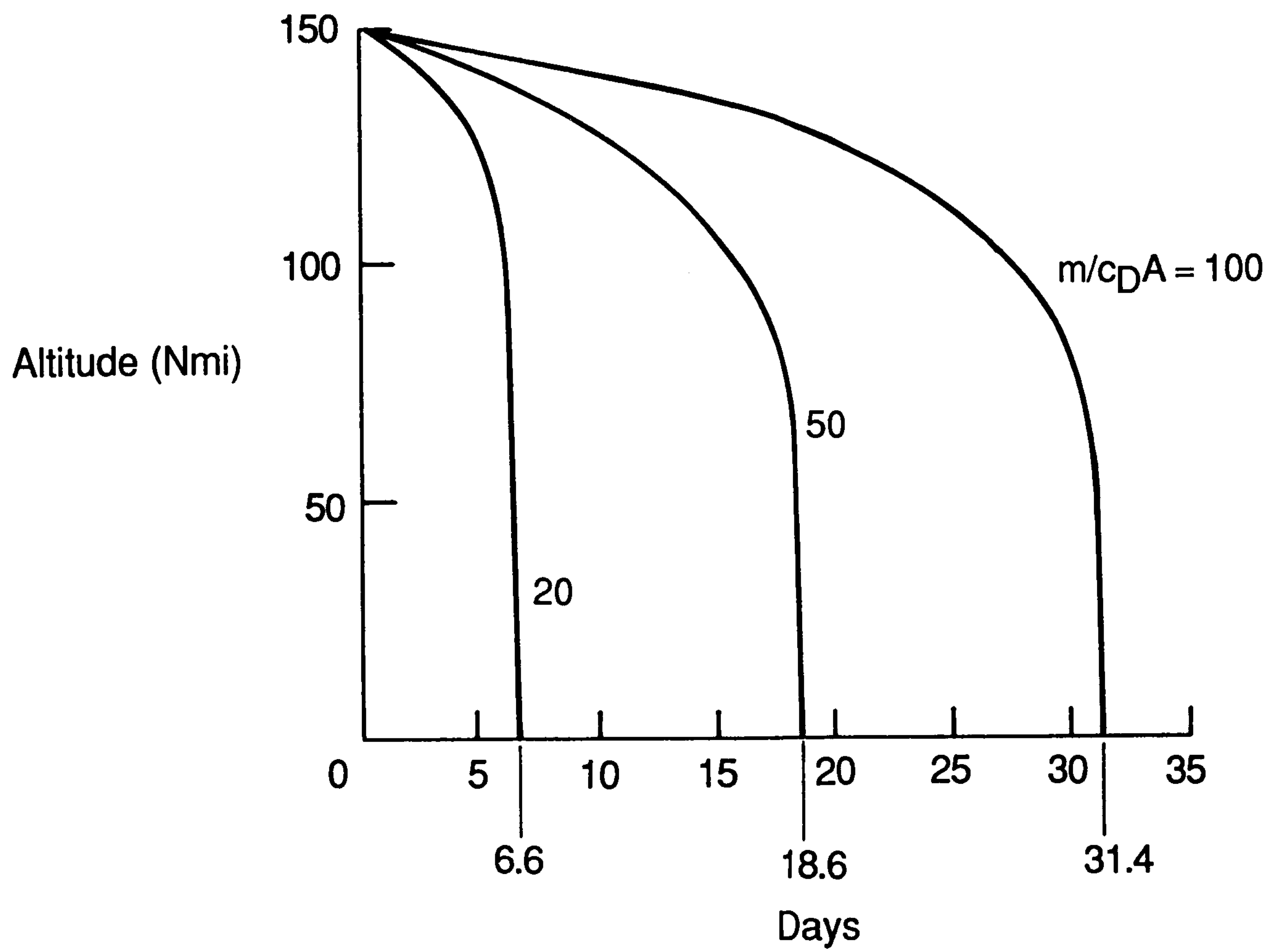

Figure C1. Orbital Decay Rates for Initial Altitude of 150 Nmi (Nominal Atmosphere) (January 15, 1993 Launch)

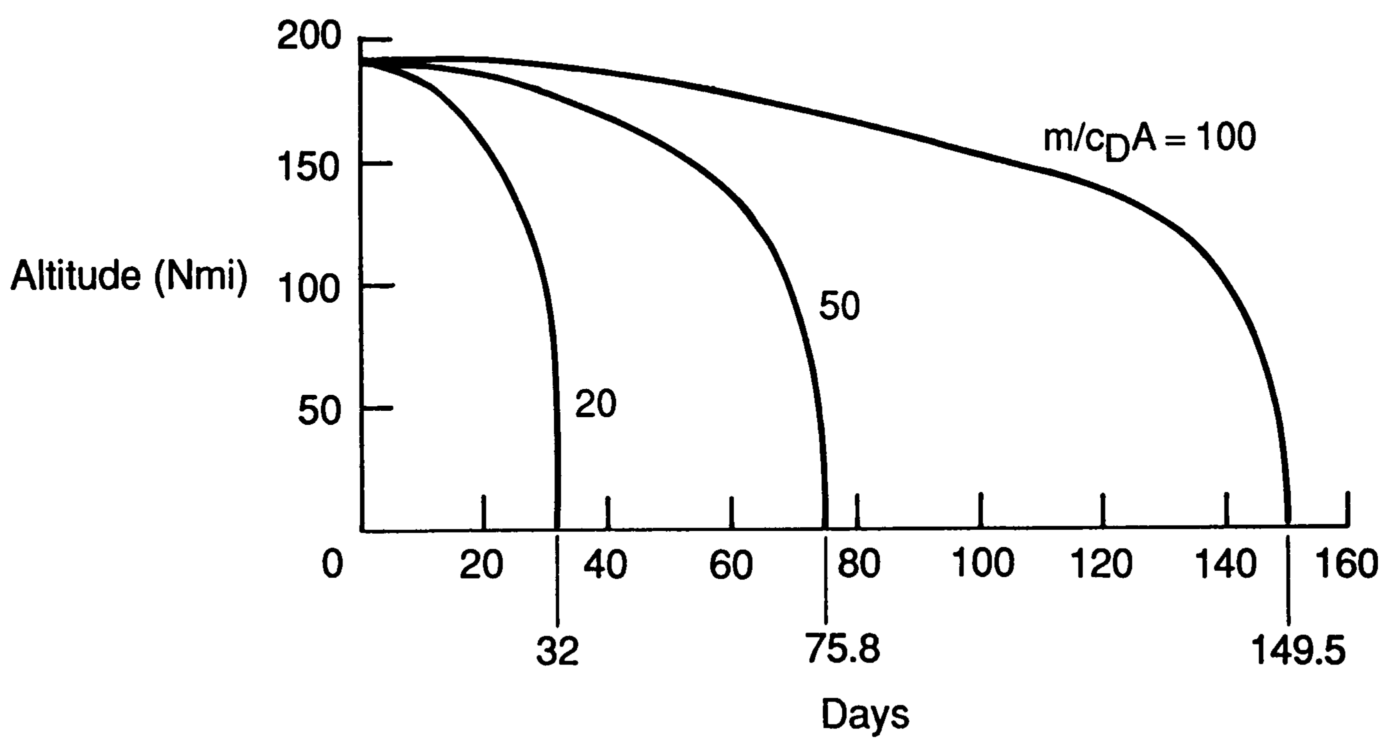

Figure C2. Orbital Lifetime for Initial Altitude of 190 Nmi (Nominal Atmosphere) (January 15, 1993 Launch)

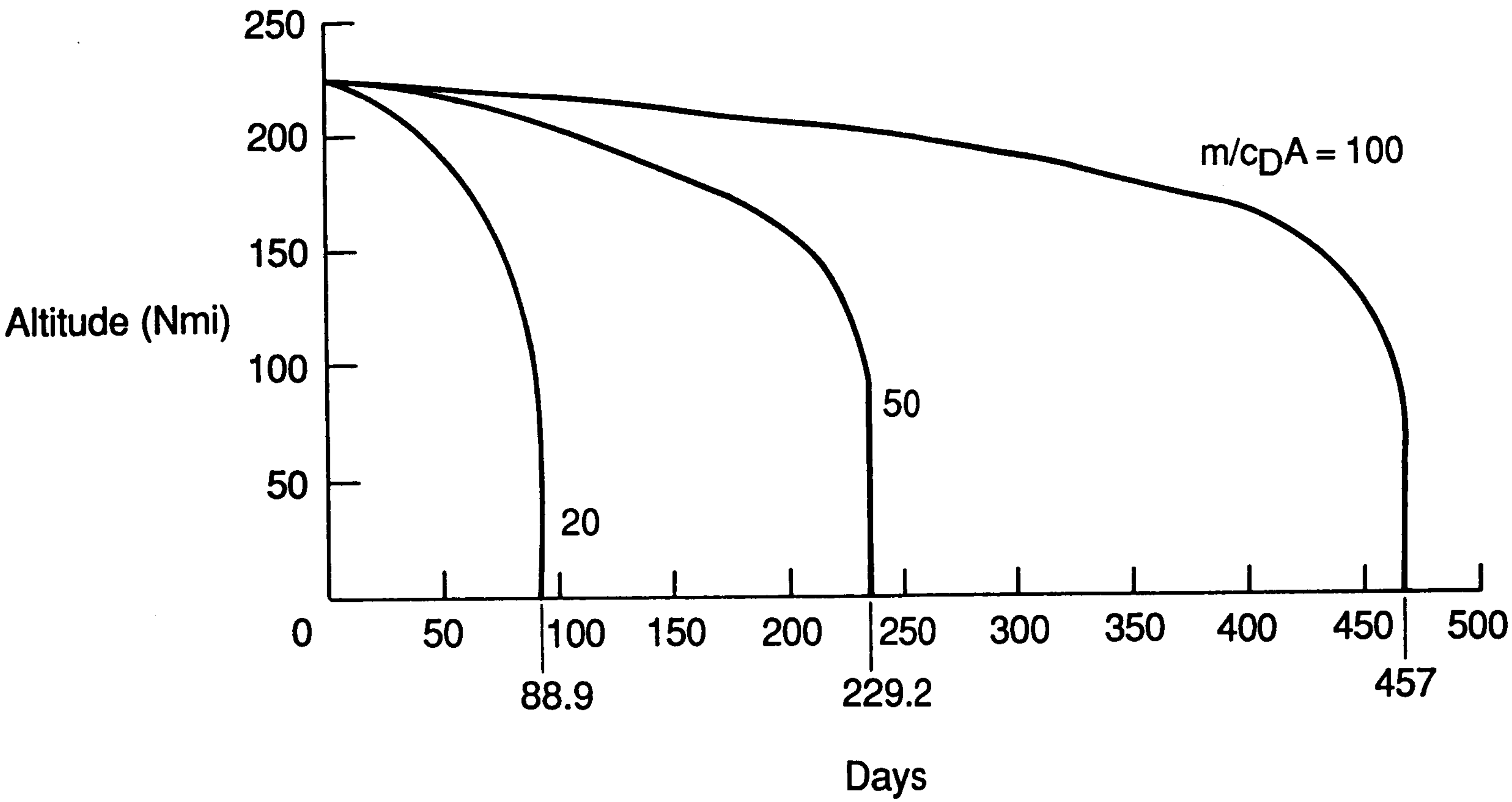

Figure C3. Orbital Lifetime for Initial Altitude of 220 Nmi (Nominal Atmosphere) (January 15, 1993 Launch)

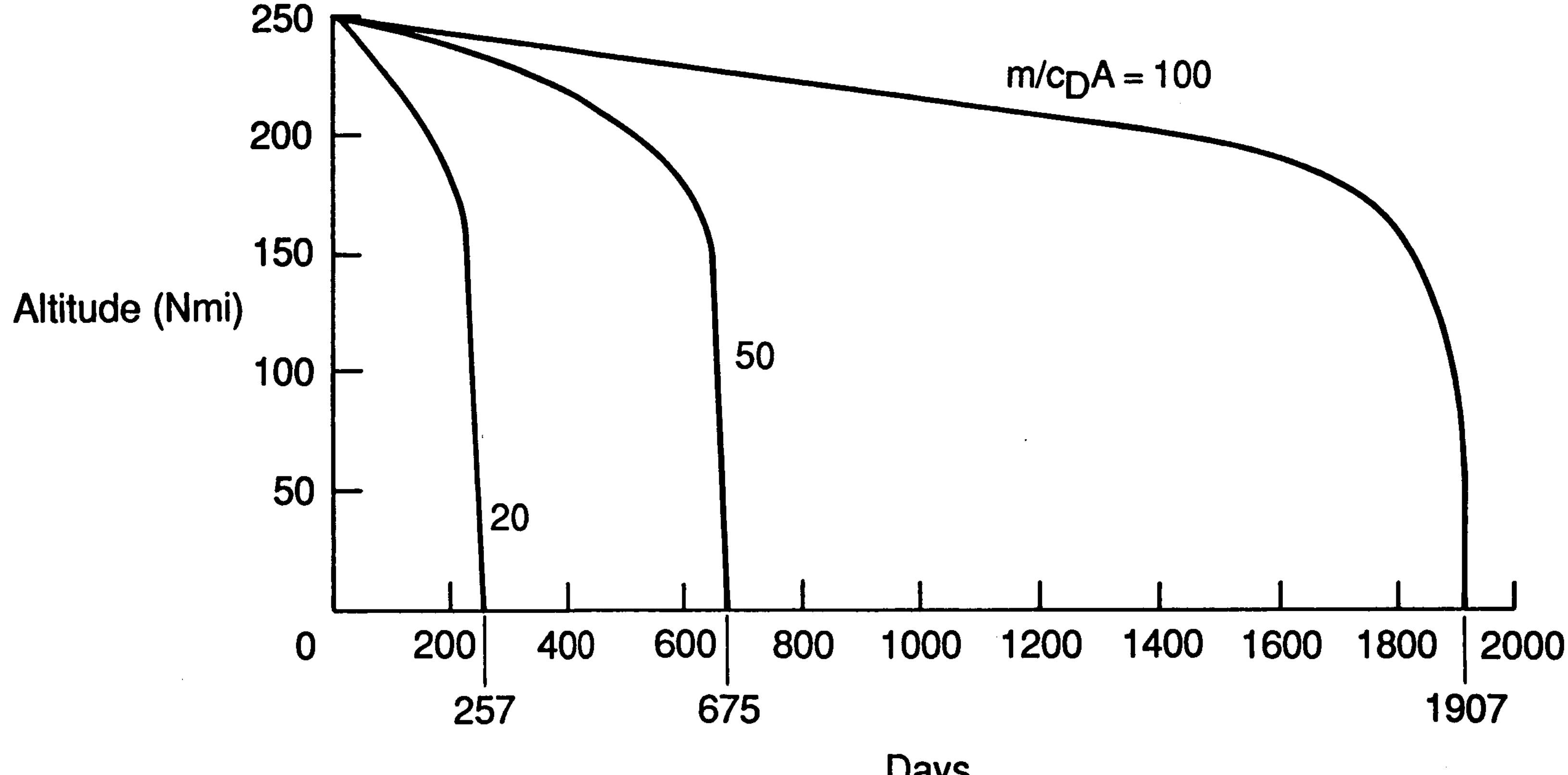

Figure C4. Orbital Decay Rates for Initial Altitude of 250 Nmi (Nominal Atmosphere) (January 15, 1993 Launch)

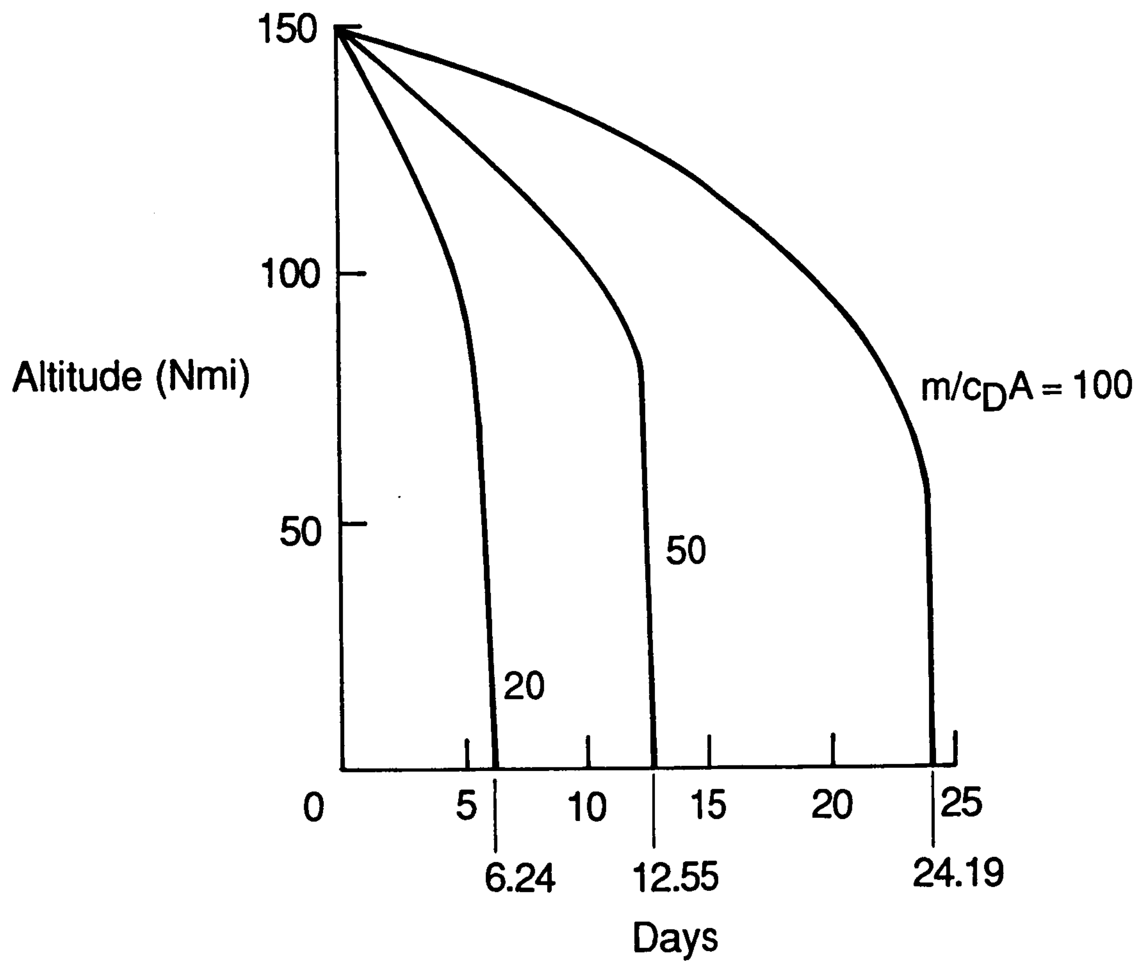

Figure C5. Orbital Lifetime for Initial Altitude of 150 Nmi (2 sigma Atmosphere) (January 15, 1993 Launch)

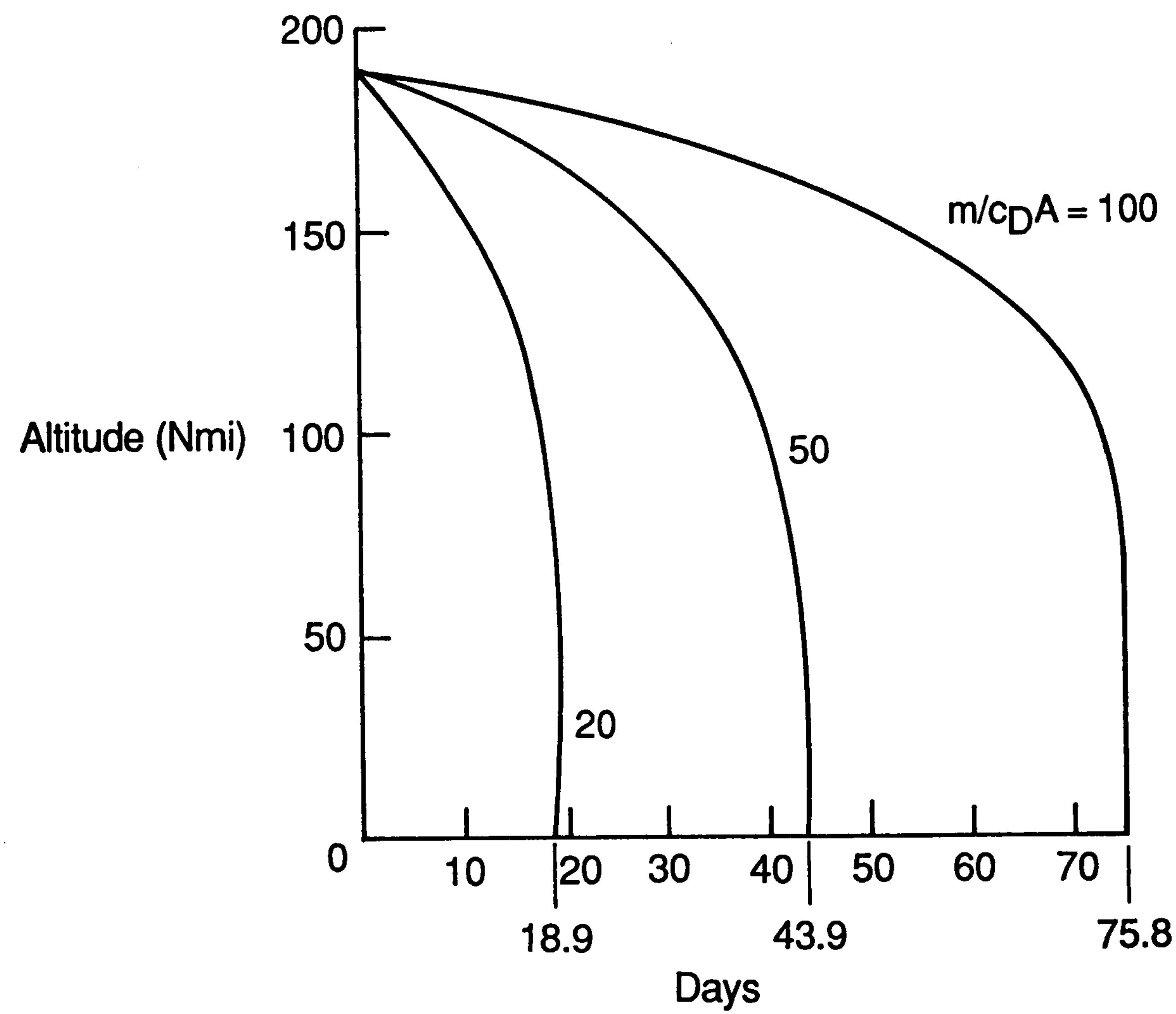

Figure C6. Orbital Lifetime for Initial Altitude of 190 Nmi (2 sigma Atmosphere) January 15, 1993 Launch)

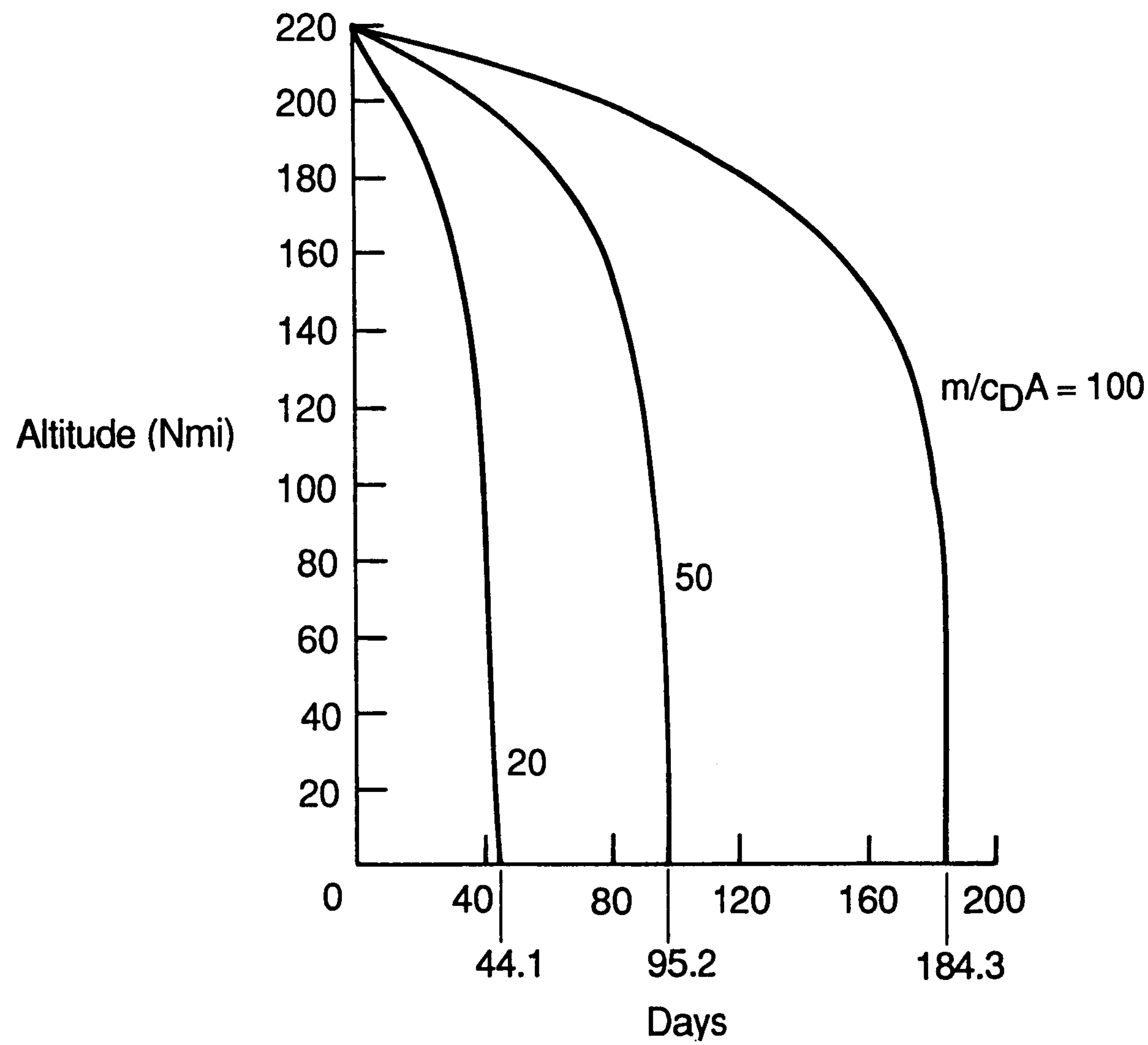

Figure C7. Orbital Lifetime for Initial Altitude of 220 Nmi (2 sigma Atmosphere) (January 15, 1993 Launch)

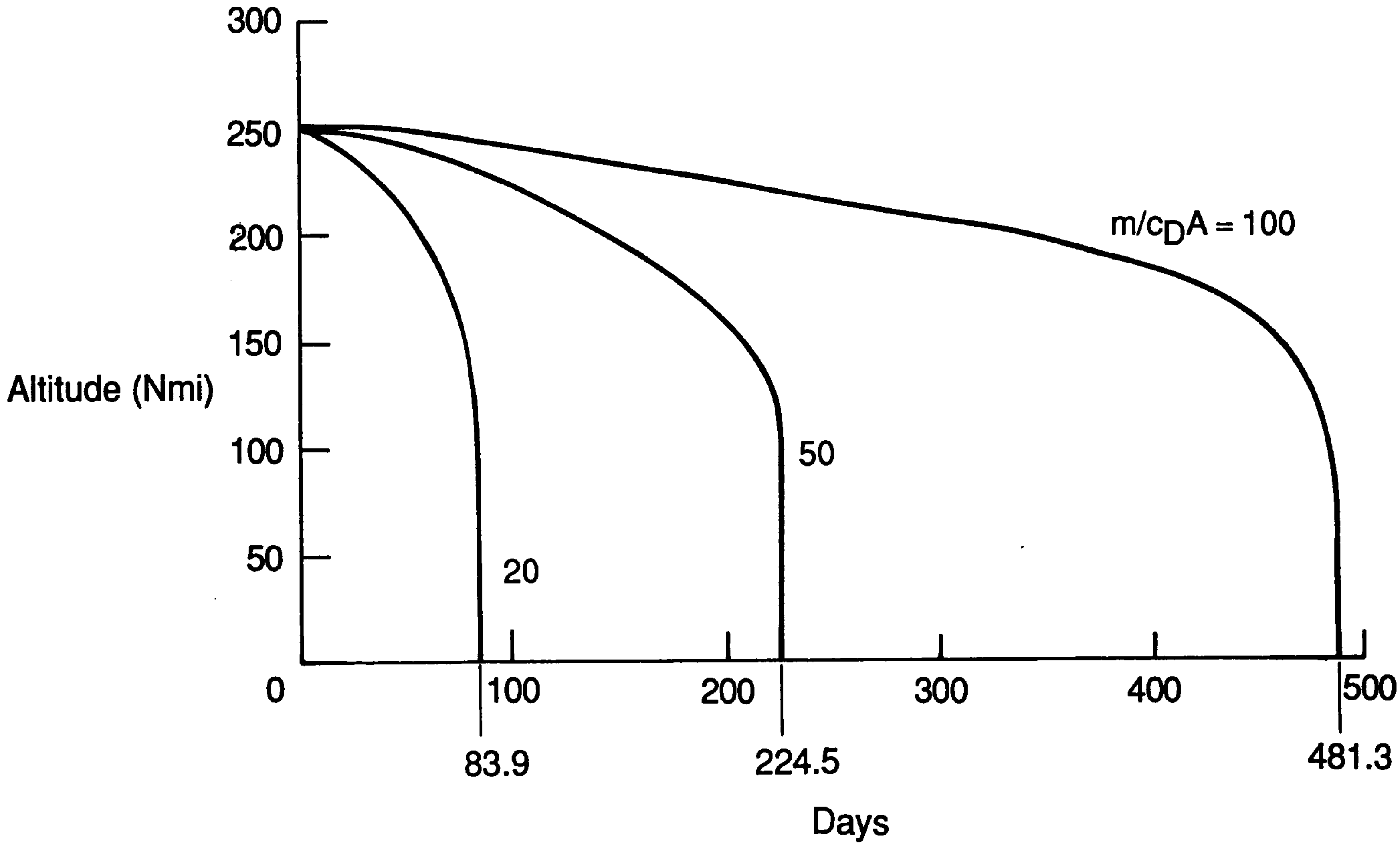

Figure C8. Orbital Lifetime for Initial Altitude of 250 Nmi (2 sigma Atmosphere) (January 15, 1993 Launch)

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16. Abstract

A design and assembly sequence was conducted on one option of the Dual Keel Space Station examined by a NASA Critical Evaluation Task Force to establish viability of several variations of that option. A goal of the study was to produce and analyze technical data to support Task Force decisions to either examine particular Option 3 variations in more depth or eliminate them from further consideration.

An analysis of the phasing assembly showed that use of an Expendable Launch Vehicle in conjunction with the Space Transportation System (STS) can accelerate the buildup of the Station and ease the STS launch rate constraint. The study also showed that use of an Orbital Maneuvering Vehicle on the first flight can significantly benefit Station assembly and, by performing Station subsystem functions, can alleviate the need for operational control and reboost systems during the early flights.

In addition to launch and assembly sequencing, the study assessed stability and control, and analyzed node-packaging options and the effects of keel removal on the structural dynamics of the Station. Results of these analyses are presented and discussed.

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